Probing New Physics with the Higgs Boson at the LHC

Ian Low

UC Irvine

References:

R. Dermisek + I.L., hep-ph/0701235

I.L. + R. Rattazzi, to appear

Outline

- Higgs boson search at the LHC
- One thousand and one models on the Higgs
- The Minimal Supersymmetric Standard Model (MSSM):

  Using the Higgs to measure the top squark sector
- Non-supersymmetric theories:

  Naturalness in the Higgs production/decay
- Conclusion

Higgs search at the LHC

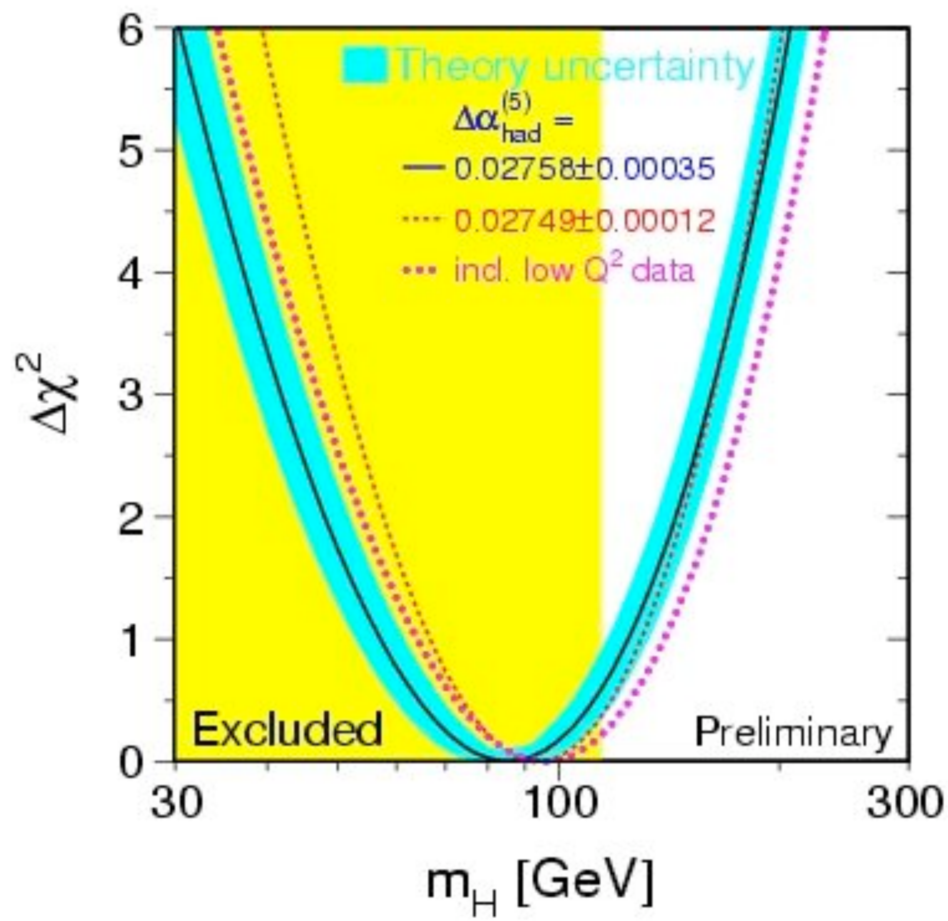
The Higgs boson is the last particle in the standard model that hasn't been observed directly!

The History:

Legacy of LEP -- precision electroweak measurements

LEPEWWG as of July 2006:

Minimal chi-square at Higgs mass = 85 GeV with an uncertainty of +39 GeV and -28 GeV



Unfortunately LEP did not see the standard model Higgs before it was shut down in 2000.

The combined four LEP experiments put a lower bound on the Higgs mass at 114.4 GeV at the 95% confidence Level. (hep-ex/0306033)

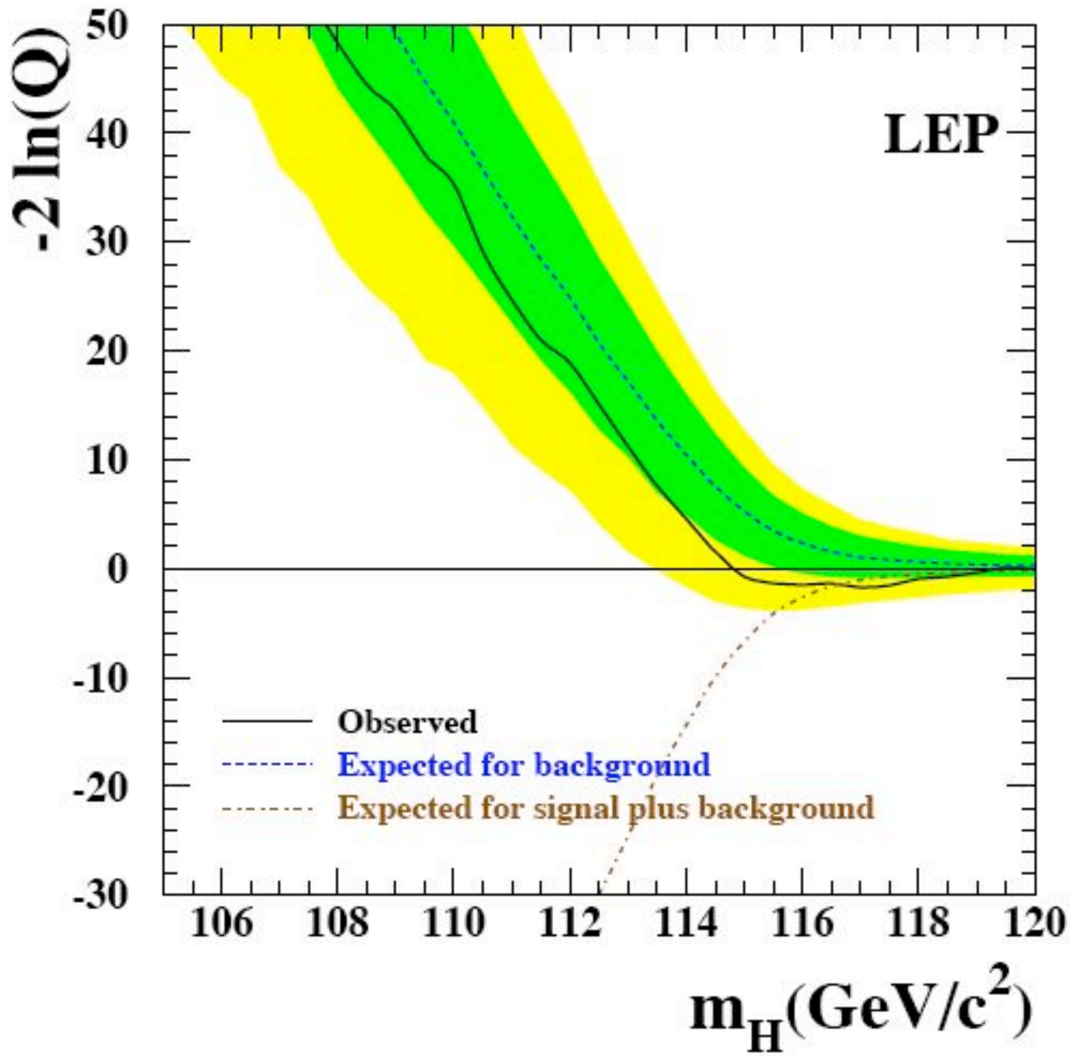
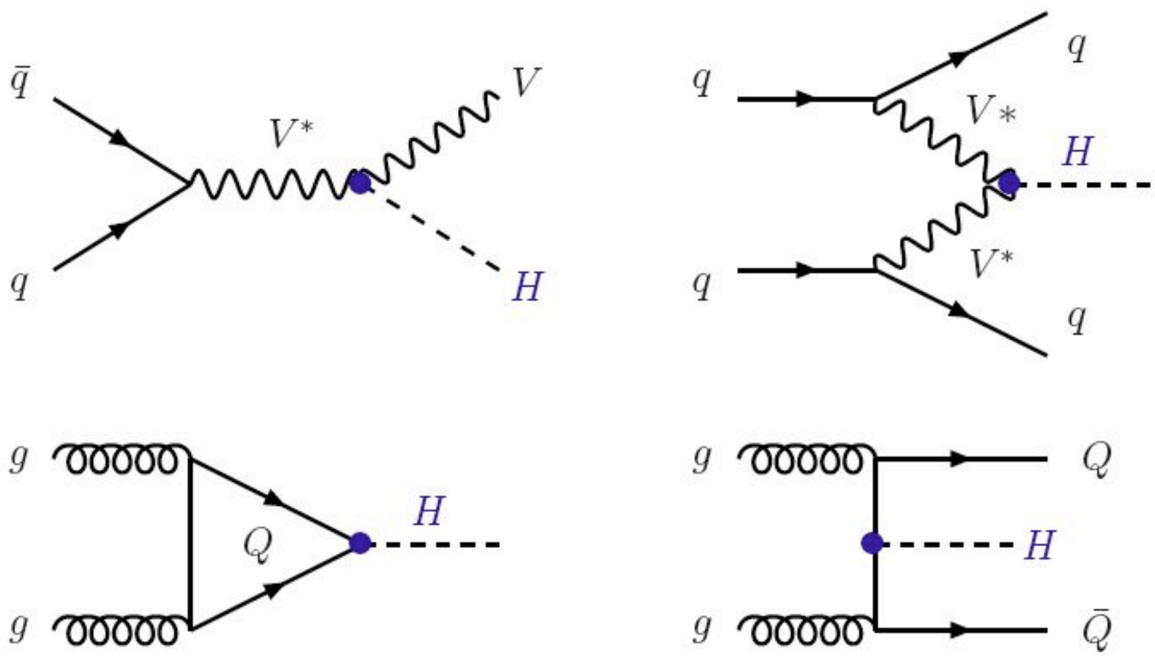


Figure 1: Observed and expected behaviour of the test statistic $-2\ln Q$ as a function of the test mass m_H, obtained by combining the data of the four LEP experiments. The full curve represents the observation; the dashed curve shows the median background expectation; the dark and light shaded bands represent the 68% and 95% probability bands about the median background expectation. The dash-dotted curve indicates the position of the minimum of the median expectation for the signal plus background hypothesis when the signal mass given on the abscissa is tested.

The focus has now shifted to LHC (and Tevatron)

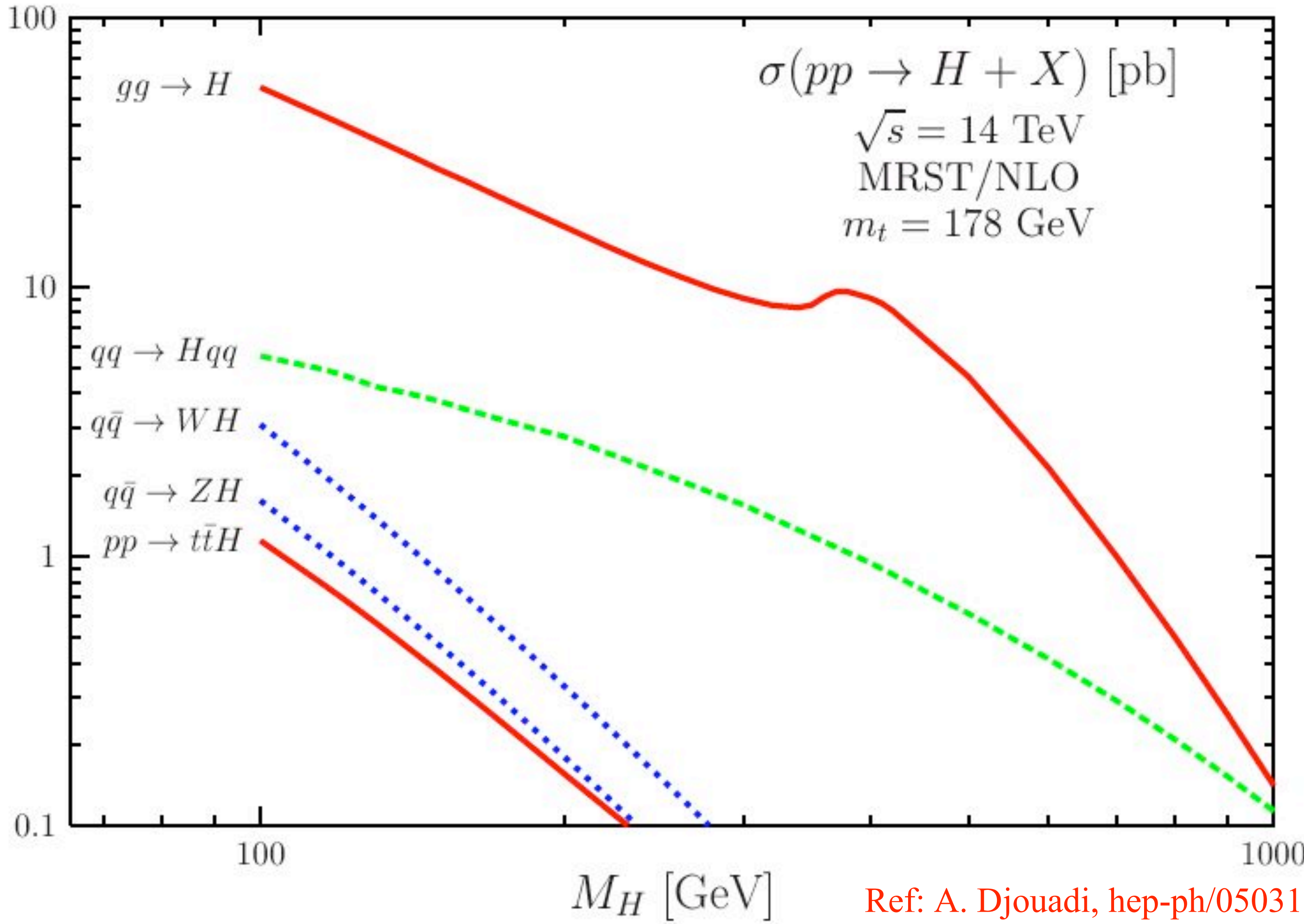
Main production mechanisms of the Higgs at the LHC (and hadron colliders in general):

$$\begin{aligned} \text{associated production with } W/Z: &\quad q\bar{q} \longrightarrow V+H \\ \text{vector boson fusion}: &\quad qq \longrightarrow V^*V^* \longrightarrow qq+H \\ \text{gluon}-\text{gluon fusion}: &\quad gg \longrightarrow H \\ \text{associated production with heavy quarks}: &\quad gg, q\bar{q} \longrightarrow Q\bar{Q}+H \end{aligned}$$



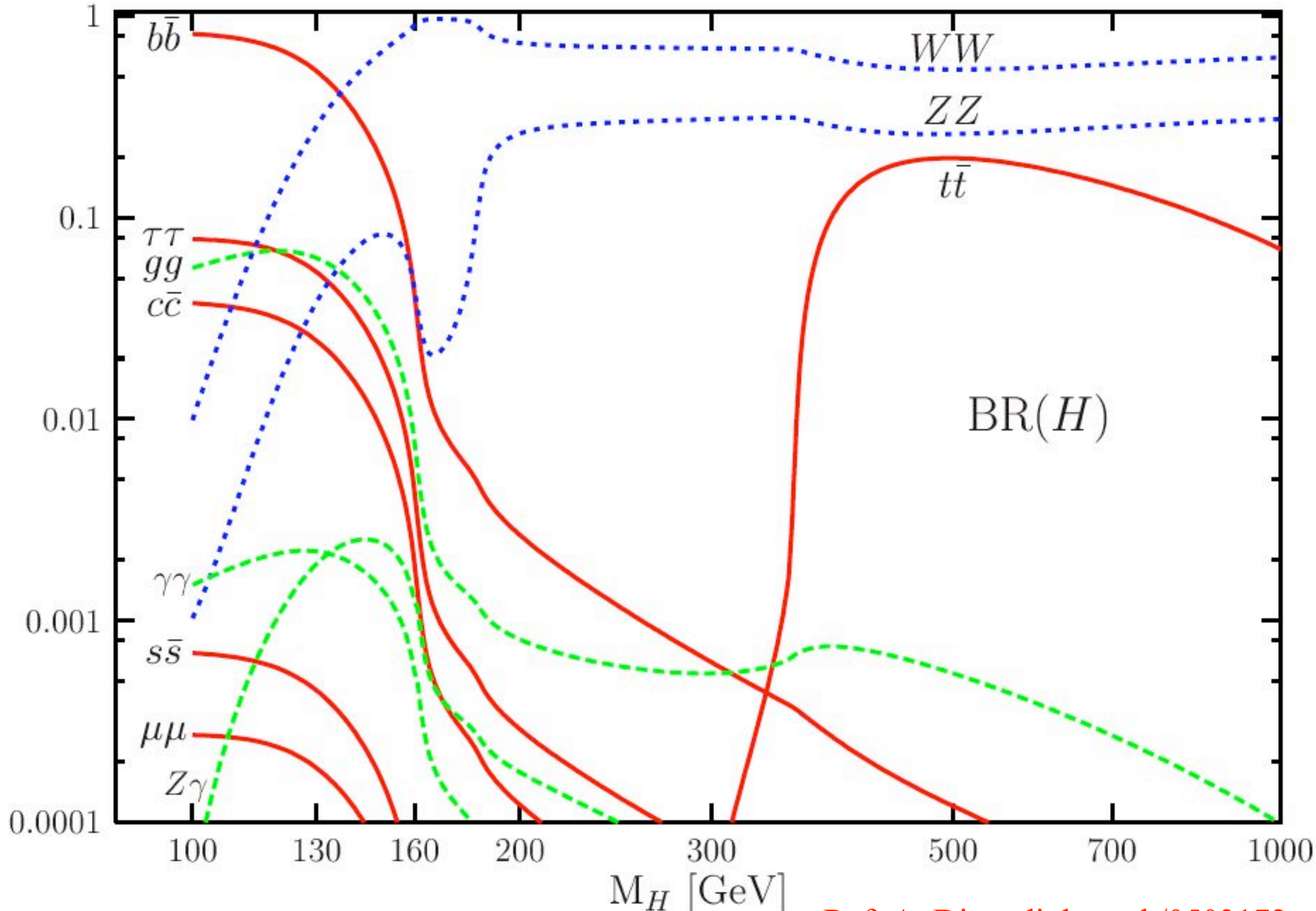
Ref: A. Djouadi, hep-ph/0503172

Among them gluon fusion is the dominant mechanism!



Ref: A. Djouadi, hep-ph/0503172

Decay channels depend on the Higgs mass:



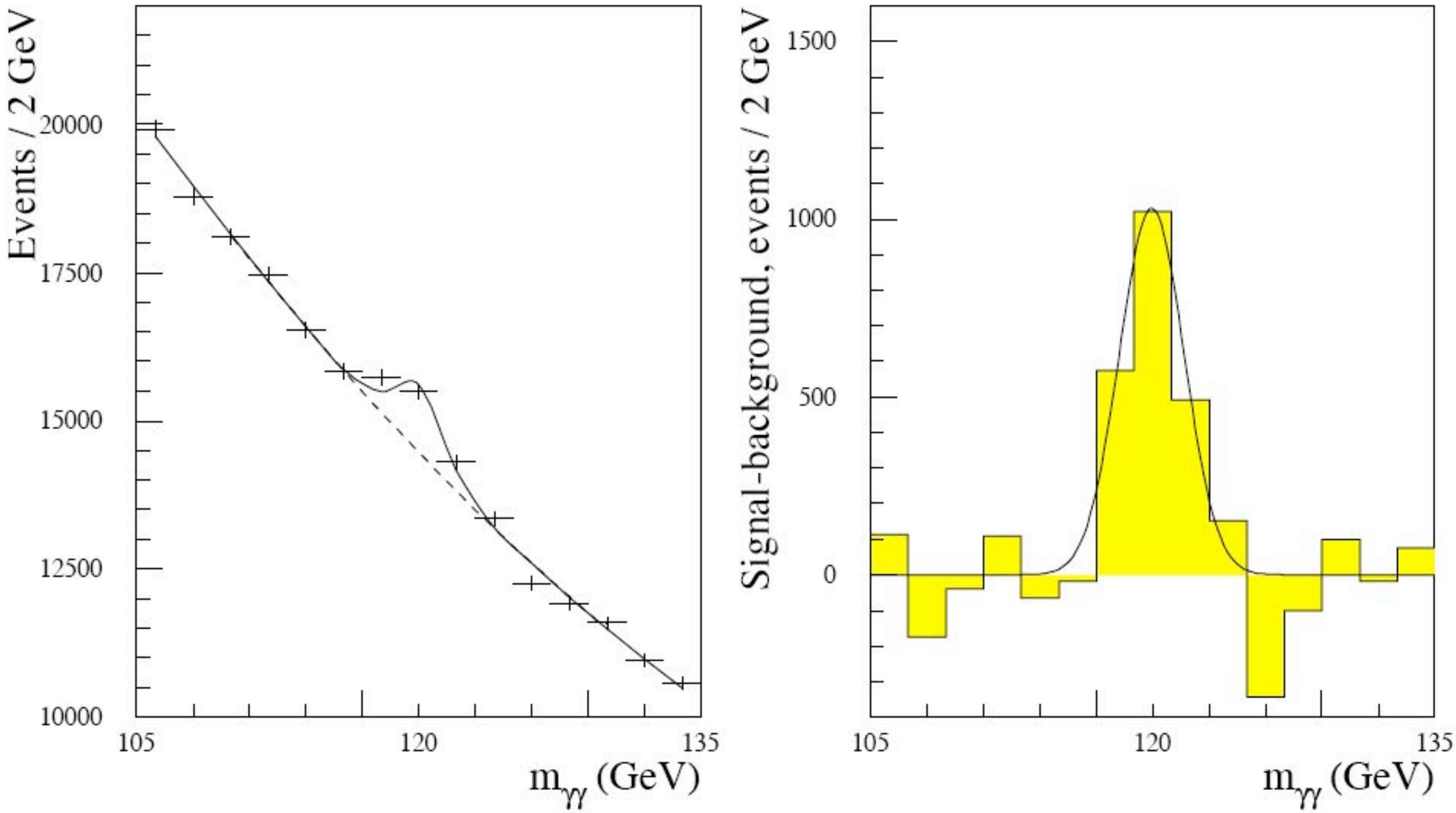
Ref: A. Djouadi, hep-ph/0503172

- For low Higgs mass $m_h \leq 150$ GeV, the Higgs mostly decays to two b-quarks, two tau leptons, two gluons and etc.

- In hadron colliders these modes are difficult to extract because of the large QCD jet background.

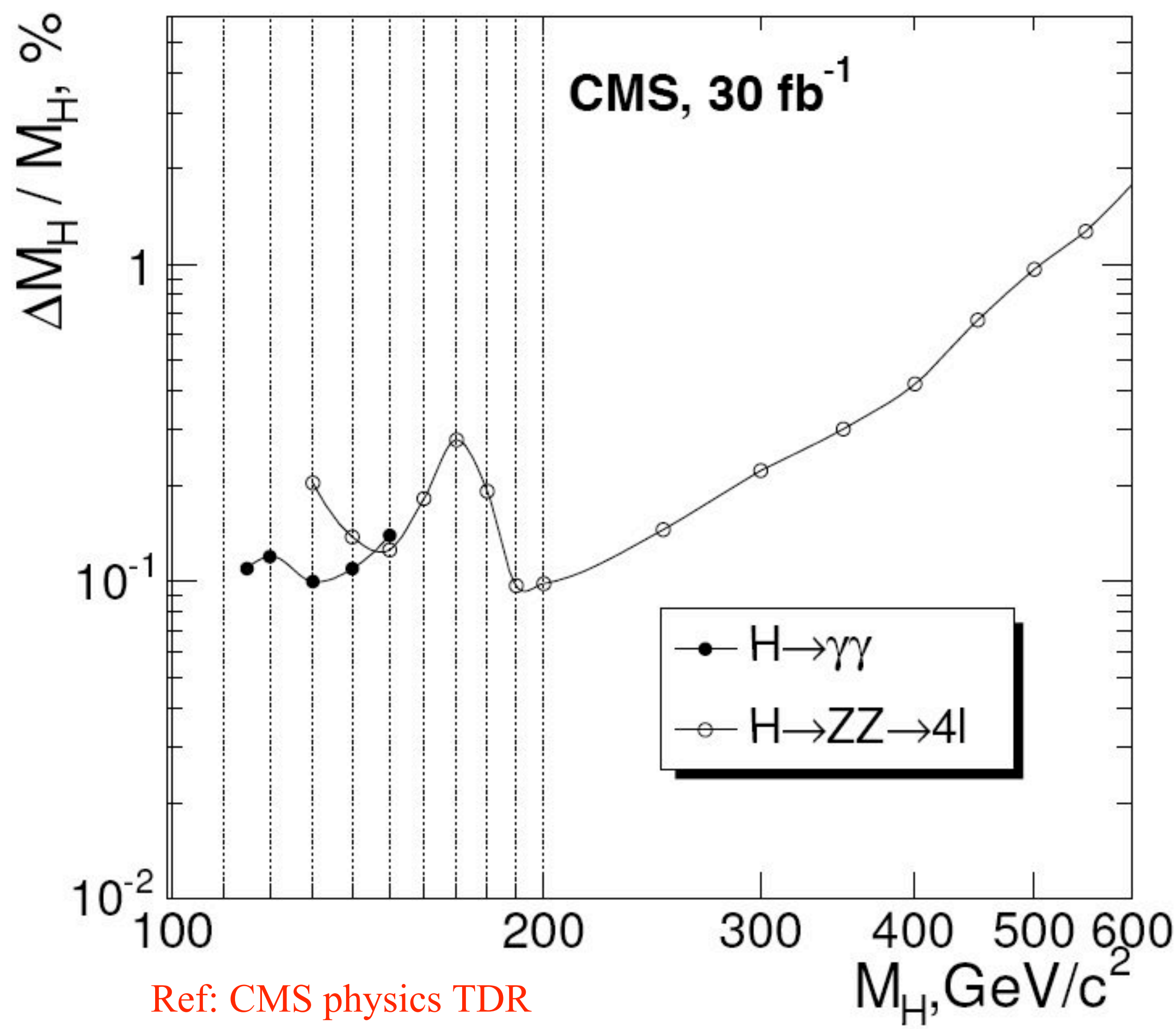
- The silver detection mode in this mass range is the two photons mode: $h \to \gamma\gamma$, which like the gluon fusion is a loop-induced process.

A simulation of a 120 GeV Higgs in the di-photon discovery channel



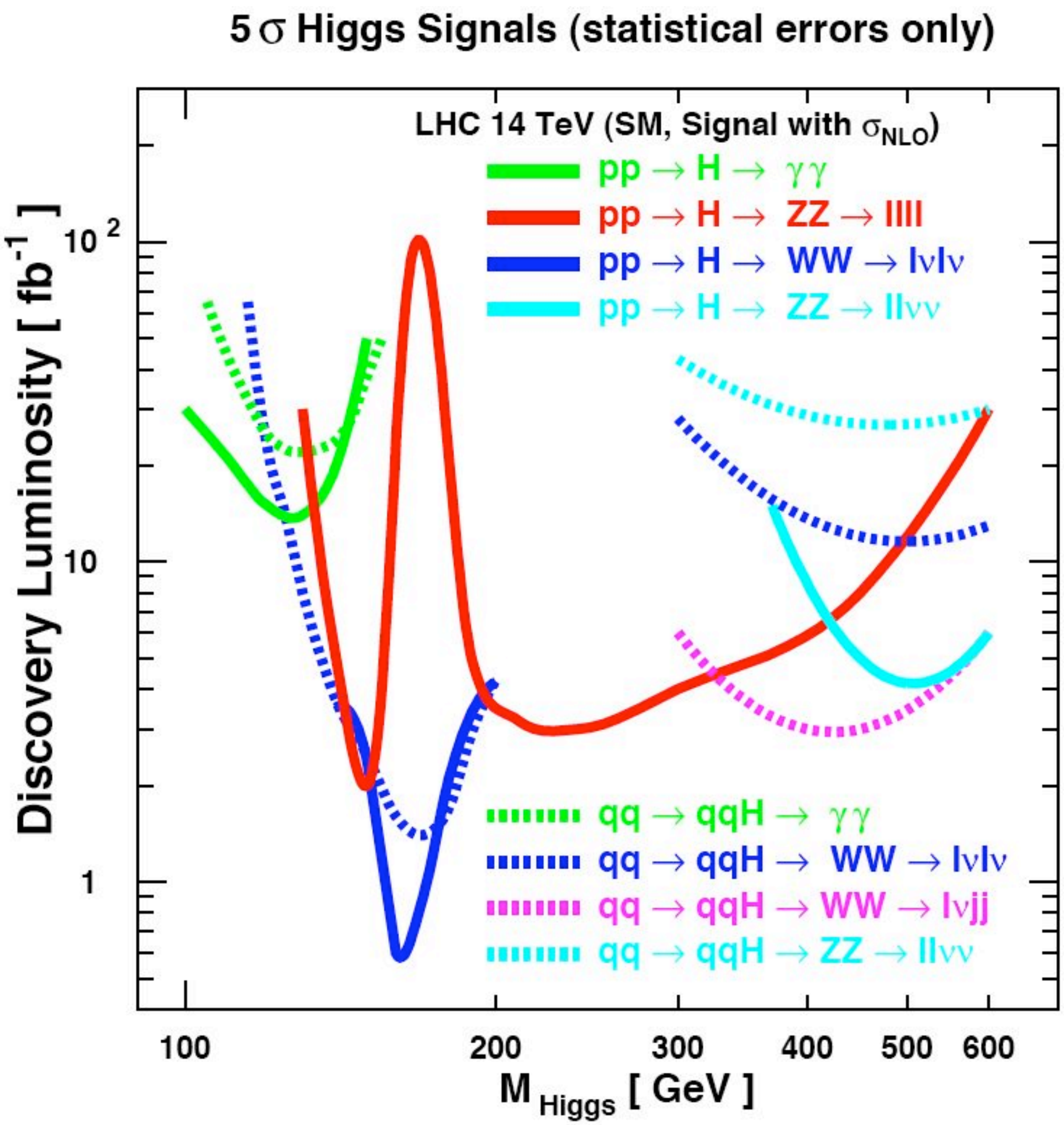
Ref: ATLAS physics TDR

Higgs mass can be measured very precisely by, for example, looking at the invariant mass of the di-photon.



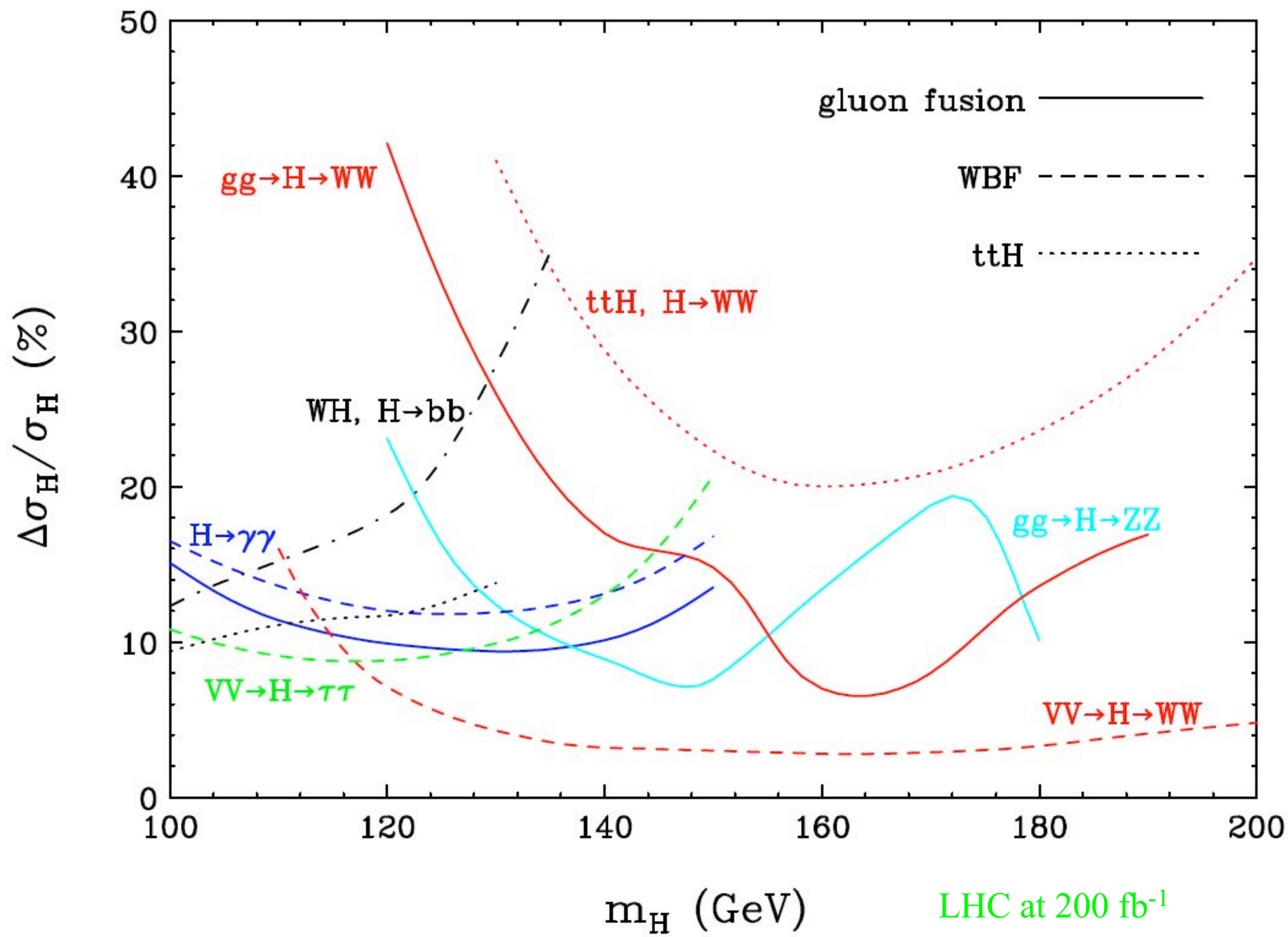
Ref: CMS physics TDR

A summary plot:



Ref: hep-ph/0208209

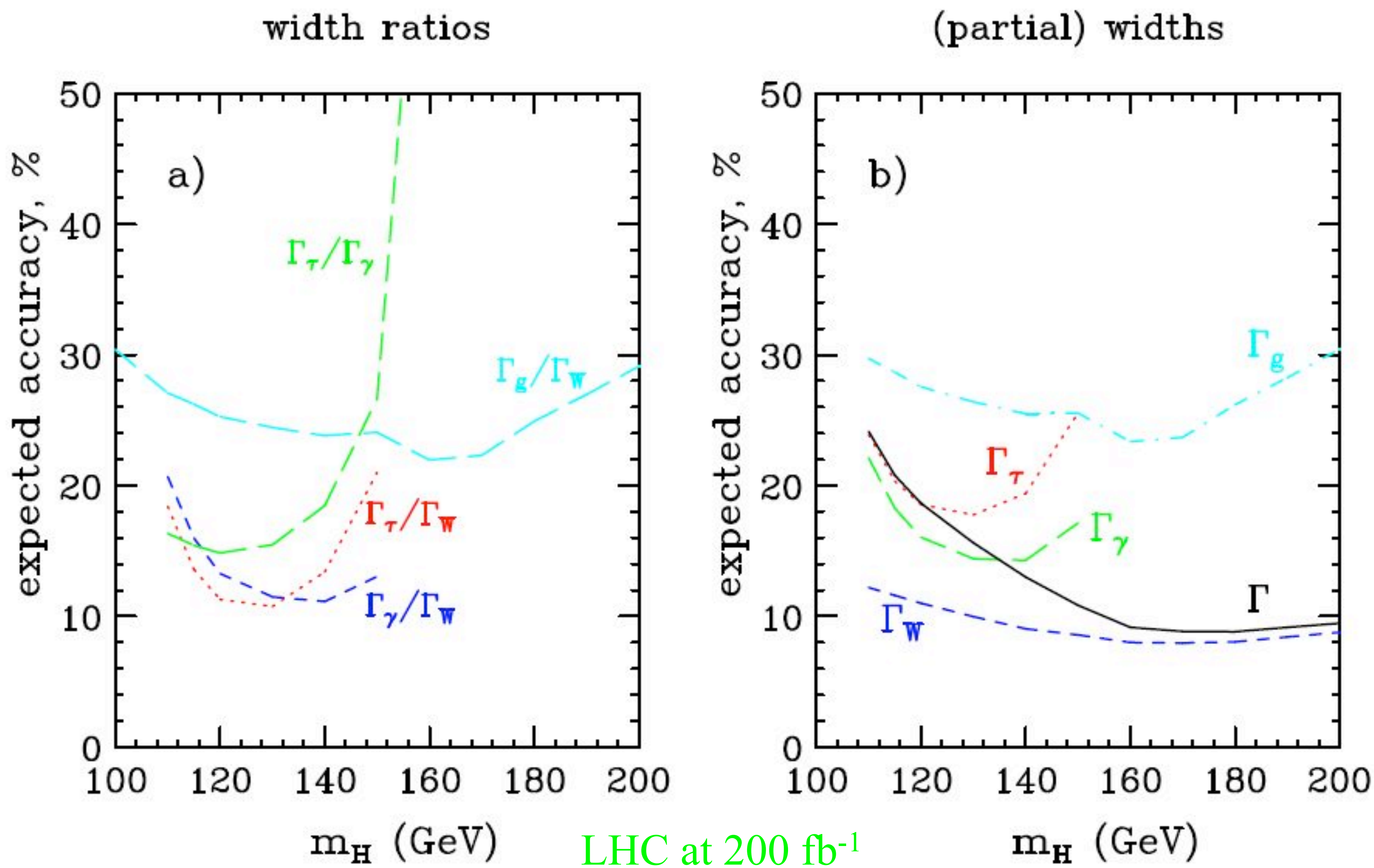
Various even rates can be measured with decent uncertainties:



LHC at 200 fb^{-1}

D. Zeppenfeld, hep-ph/0203123

Furthermore, it is possible to extract individual partial width of the Higgs boson, although with larger uncertainties.



LHC at 200 fb^{-1}

D. Zeppenfeld, hep-ph/0203123

Message to take away:

- Dominant production mechanism at the LHC is through the gluon fusion process.

- The Higgs mass can be measured very precisely at the order of 0.1%.

- The event rate of $gg \to h \to \gamma\gamma$ can be measured with 10% uncertainty, whereas for gluon fusion production rate the uncertainty is roughly 30%. For the di-photon partial width it is about 15%.

One thousand and one models on the Higgs

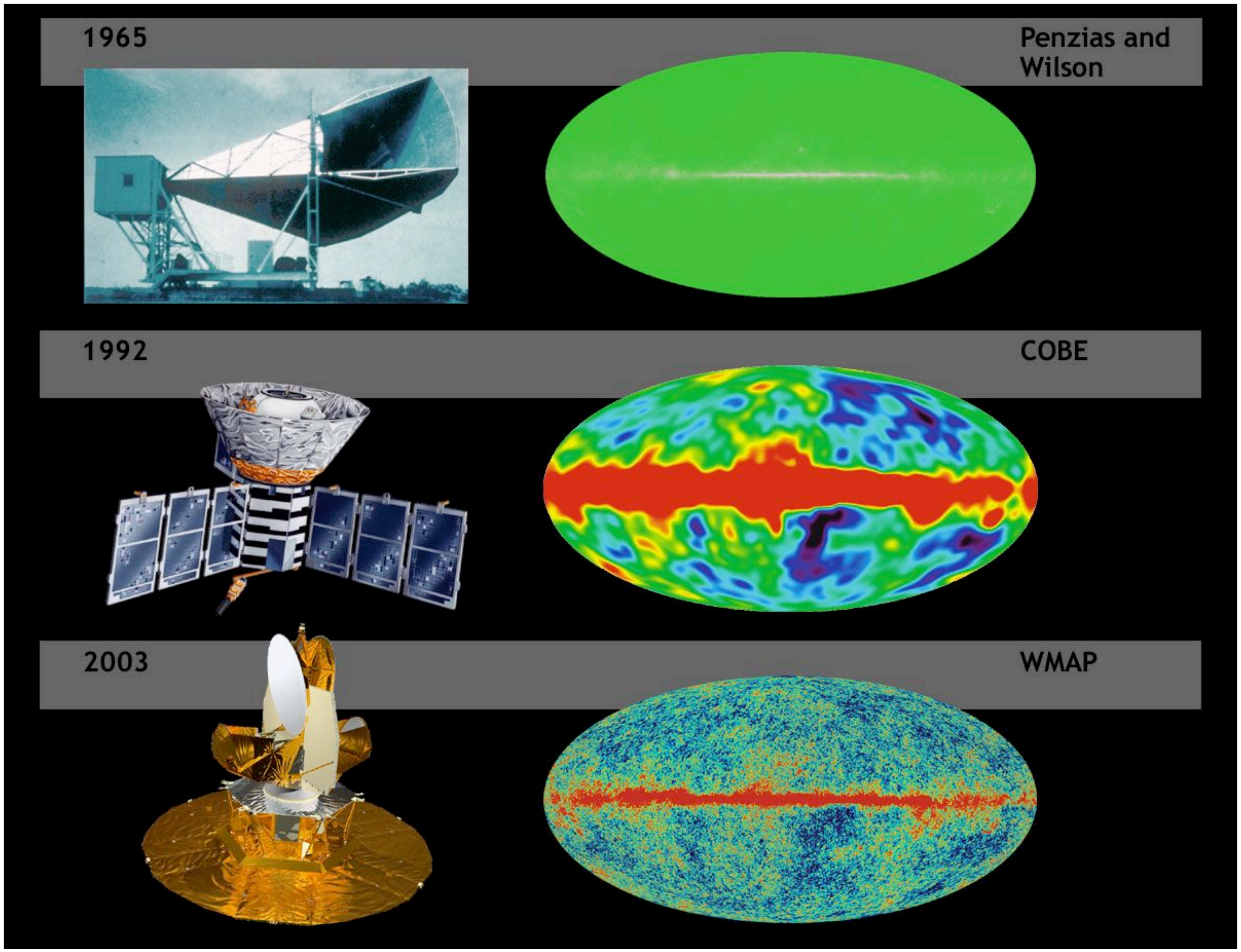
- The standard model of particle physics agrees with all collider experiments to date to high precision, yet many of us believe it must be wrong (at the TeV scale)!

- The Higgs boson is very special in the standard model because it is the only scalar. At quantum level its mass is quadratically sensitive to the scale of new physics:

$$\delta m_h^2 \propto \frac{1}{16\pi^2}\Lambda_{\rm UV}^2$$

Must be new physics at the TeV scale to have a “natural” Higgs mass at a few hundreds GeV.

- A (perhaps) better reason for physics beyond standard model is the empirical evidence, from experiments on the largest distance scale.



Revolutionary insights from Precision Cosmology

- Compelling evidence for non-baryonic dark matter
- An accelerating expansion of the Universe due to some dark energy
- Neutrino oscillations
- Cosmic baryon asymmetry
- Nearly scale-invariant, adiabatic, and Gaussian density fluctuations favored by inflation
- Etc.

Surprisingly, none of the above can be accommodated by standard model alone!

The standard model of particle physics seems like a failure from this (dark) perspective

Theorists have come up with all kinds of (crazy) models for the Higgs and physics at the TeV scale. There are many ways to slice this "space of models":

- W-W boson scattering is unitarized by spin-1 particles:

  theories without a Higgs boson such as technicolor (composite vectors), Higgsless (KK-vectors), etc.

- W-W boson scattering is unitarized by spin-0 particles:

  all theories which has a Higgs boson.

Theorists have come up with all kinds of (crazy) models for the Higgs and physics at the TeV scale. There are many ways to slice this "space of models":

- Supersymmetric theories:

  minimal supersymmetric standard model (MSSM) and its cousins like Next-to-MSSM (NMSSM), nearly MSSM (nMSSM), uMSSM …..

- Non-supersymmetric theories:

  technicolor, Higgsless theories

  composite Higgs boson (little Higgs, holographic Higgs, twin Higgs, gauge-Higgs unification, etc.)

  warped extra-dimensional models (Randall-Sundrum),

  flat extra-dimensions. (Universal Extra-dimensions (UEDs))

- One important discriminator in model-building is the "naturalness":

  whether there're new degrees of freedom and new symmetries that keep the Higgs light at O(100 GeV) naturally (such as supersymmetry, composite Higgs, etc.)

  or there're new degrees of freedom but the divergence in the Higgs mass is *not* cancelled. In these cases Higgs is light by accident. (UEDs, some warped extra-dimensional models.)

Message to take away:

- There are good reasons, both theoretical and empirical, to expect new physics, in addition to the Higgs boson, at the TeV scale.

- There are many different models for physics beyond the standard model; some are natural and some are not.

  -- sort of like cosmology in the early days: 10 theorists would come up with 14 models for TeV scale physics.

- The Higgs boson plays an essential role in many theories beyond the standard model.

MSSM: Use Higgs to measure the top squarks

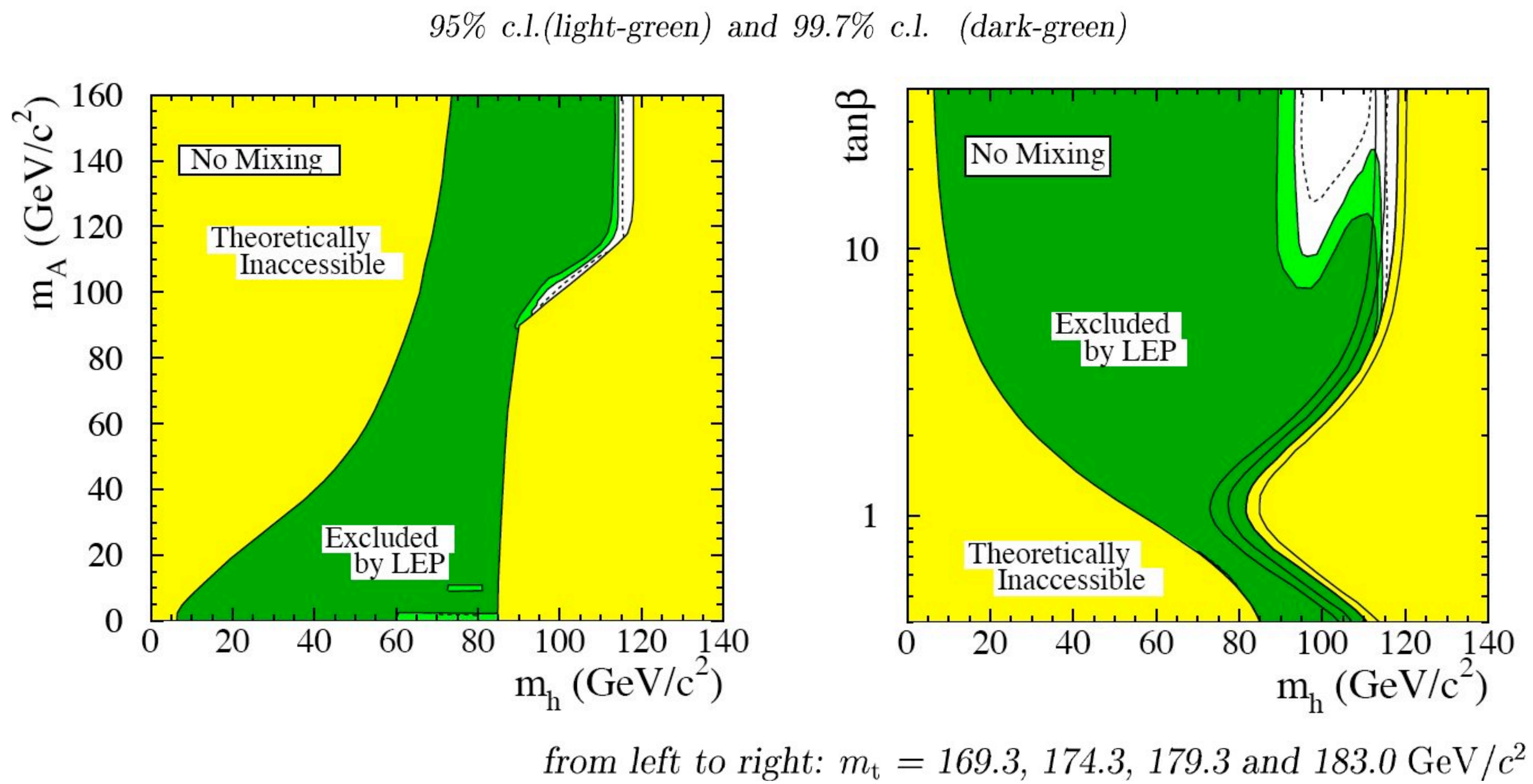
- MSSM is the most studied supersymmetric models. It has many virtues, but not without (pretty serious) vices.

  Perhaps the most severe one is the experimental constraints because we haven't observed either the Higgs or any of the superparticles.

- LEP closed up much of the "natural region" of parameter space for MSSM, and the Higgs mass in MSSM is getting fine-tuned at a few percents level.

In terms of parameter space, MSSM is really getting squeezed!

In the “no mixng” benchmark scenario:



LEP Higgs working group, 2005

- The root of the problem: in MSSM at leading order in perturbation,

$$m_h \le m_Z |\cos 2\beta| \le m_Z = 91\ \mathrm{GeV}$$

whereas the LEP bound is Higgs mass > 114 GeV!

- Subleading contributions from the top squarks (stops!), which have the strongest couplings with the Higgs boson, must be large.

  (To a much less extent the bottom squarks (sbottoms) come in second.)

- There are two stops in MSSM, labeled as the left-handed and right-handed, which mix after electroweak symmetry breaking and become stop1 (the lighter) and stop2 (the heavier).

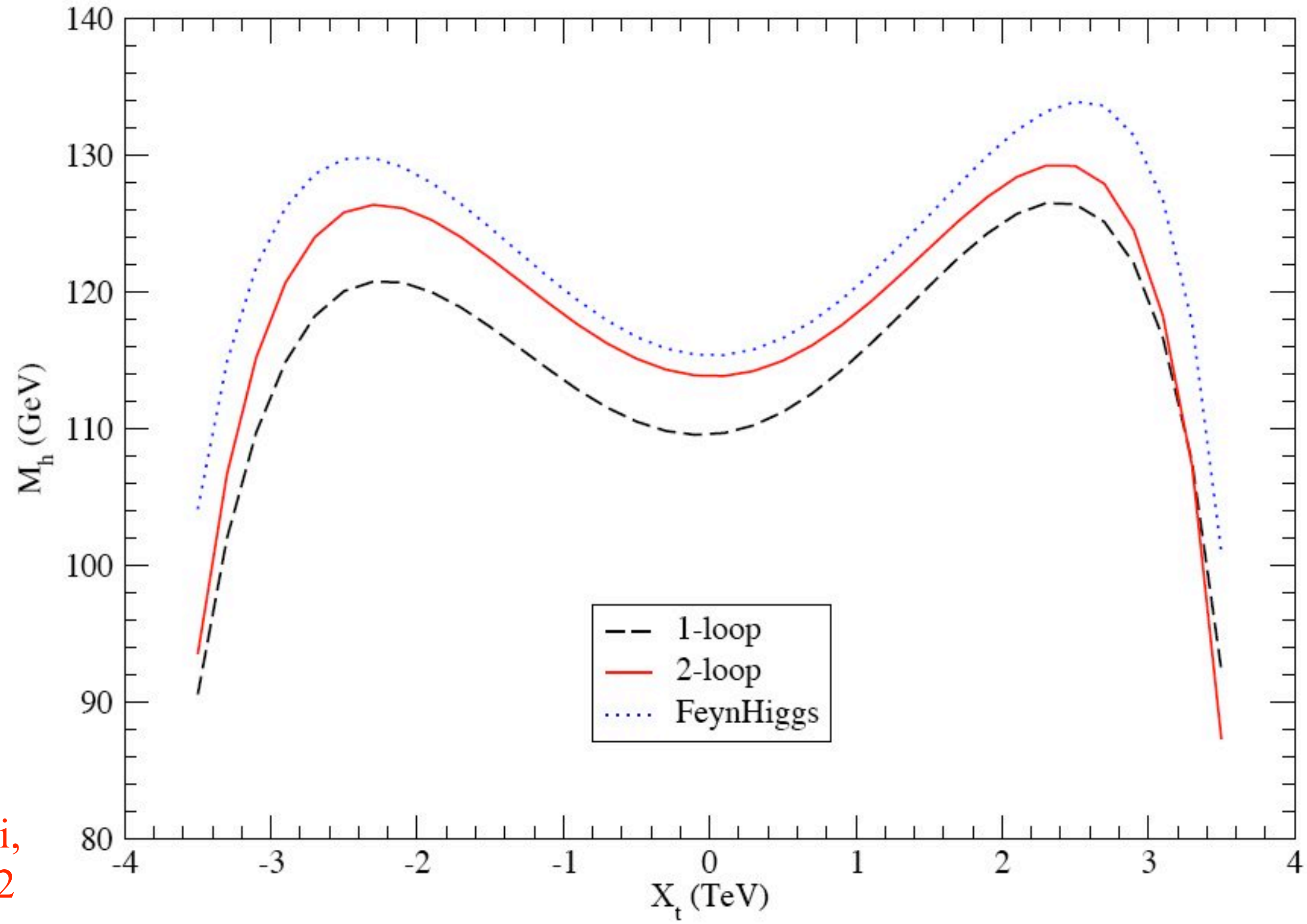
- The mass-squared matrix is real and symmetric -- there're three independent parameters:

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_{\tilde{t}_L}^2 + m_t^2 + D_L^t & m_t X_t \\ m_t X_t & m_{\tilde{t}_R}^2 + m_t^2 + D_R^t \end{pmatrix}$$

$$\begin{aligned} D_L^t &= \left(\frac{1}{2} - \frac{2}{3}s_w^2\right) m_Z^2 \cos 2\beta \\ D_R^t &= \frac{2}{3}s_w^2 m_Z^2 \cos 2\beta \\ X_t &= A_t - \frac{\mu}{\tan\beta} \end{aligned}$$

- There are two ways to make the Higgs mass larger than 114 GeV:
  - Large diagonal entries and small off-diagonal entry. Stops are heavy at around 1 TeV and roughly degenerate.
  - Small diagonal entries and large off-diagonal. Stops are light at a few hundred GeVs and mass splitting is large.

Plot of Higgs mass versus the mixing (off-diagonal) term:



Ref: A. Djouadi, hep-ph/0503172

Figure 1.4: The lighter MSSM Higgs boson mass as a function of X_t in the $\overline{\rm DR}$ scheme for $\tan\beta = 10$ *and* $M_S = M_A = 1$ *TeV with* $m_t = 178$ *GeV. The full and dashed lines correspond, respectively, to the two–loop and one–loop corrected masses as calculated with the program* `SuSpect`, *while the dotted line corresponds to the two–loop* M_h *value obtained in the Feynman diagrammatic approach with* `FeynHiggs`; *from Ref. [121].*

- Some theorists try to argue that “light stops, large mixing” scenario is a less fine-tuned region of MSSM.
- Theoretically it’ll be important and interesting to distinguish between the two possibilities:
  – Heavy stops, no mixing. (Unnatural. Higgs mass is fine-tuned.)
  – Light stops, large mixing. (Still unnatural, but less unnatural.)

An important question: How do we measure the stop masses and mixing angle?

(Naïve) Answer: study stops in the production/decay processes at the LHC and measure their properties.

Well, life is not so simple….

Three factors complicate the measurement in direct production processes:

1. MSSM with R-parity has a dark matter candidate that is usually neutral and escapes detection. Moreover, superpartners are pair-produced.

   There is large missing transverse energy (E_T) in each event!

The implications:

Event-by-event basis for mass reconstruction is impossible.

Need to resort to kinematic endpoints and edges in the invariant mass distributions, whose locations depend on ALL particles involved in the decay chain, including the missing particles.

Three factors complicate the measurement in direct production processes:

2. The LHC is a hadron collider with proton-proton collisions.

   It is the partons inside the protons that are colliding and interacting with one another.

   That is we do not know the total center-of-mass energy in each collision. Therefore there is no kinematic constraint to impose in the longitudinal direction of the collision.

Three factors complicate the measurement in direct production processes:

3. A typical event has multi-jet, multi-lepton, and missing E_T .

   Sometimes a long decay chain is involved. It is difficult to figure out which jet/lepton is associated with a particular decay chain.

   Therefore we need to sum over all the possibilities and usually a large combinatorial factor follows.

In the end, it is a complicated and elaborate analysis to extract SUSY masses from direct production/decay processes.

A lot of assumptions, such as whether or not a particular decay channel is open, are involved.

Extraction of one particular mass parameter depends crucially on many external factors such as prior knowledge of other SUSY masses.

Mixing angle is especially difficult to extract; measurements of mass eigenvalues wouldn't help.

For top squarks even more efforts are required, due to the reconstruction of top quarks in the process.

- This is a situation where the Higgs comes in to rescue.

- The Higgs boson is a very useful probe for the stop sector because stops, being partners of the top quarks, have significant couplings to the Higgs.

- Need measurements where stop contributions could be important.

  $\rightarrow$ Higgs mass and production rate in the gluon fusion channel are exactly what we ordered!

When only the stops are important:

1. Both the Higgs mass and production rate in MSSM depends very little on supersymmetric parameters other than those in the stop sector as long as

$$10 \leq \tan\beta \leq m_t/m_b$$

$$|m_b \mu \tan\beta| \leq m_{\tilde{b}_L},\, m_{\tilde{b}_R}$$

2. If tan β is large and μ becomes sizable simultaneously, the sbottom effect is important.

3. Will also stay in the “decoupling limit,” where the MSSM Higgs sector is standard model-like.

- There are three parameters in the stop mass matrix. A priori we might expect it is only possible to constrain the three parameters on a one-dimensional surface with two measurements.

- It turns out that there is a (almost) flat direction; if the ratio

$$|r| = \left| \frac{m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R}}{m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R}} \right| \leq 0.4$$

then both the mass and production rate depends on only

$$m_{\tilde{t}} = \frac{1}{2}(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R}), \quad X_t$$

- In the end two measurements give two numbers!

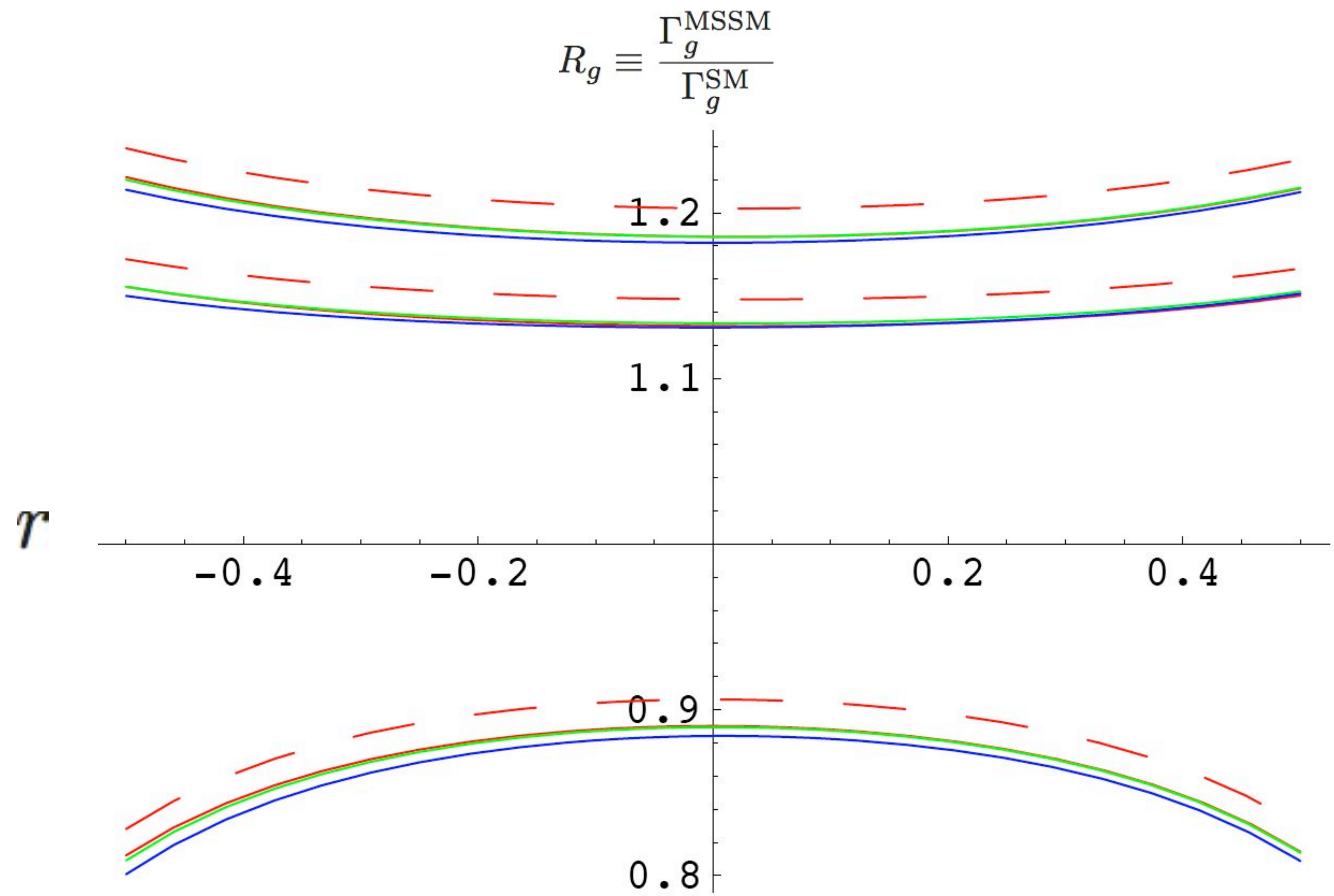


FIG. 2: Plot of R_g as a function of r for $m_{\tilde{t}}^2 = 500$ GeV, $\tan\beta = 10$ (red), $\tan\beta = 30$ (green), $\tan\beta = 50$ (blue) and $X_t/m_{\tilde{t}} = 0, -1, -2$ ordered from top down. The solid lines are $m_S = 400$ GeV and dashed lines are $m_S = 800$ GeV.

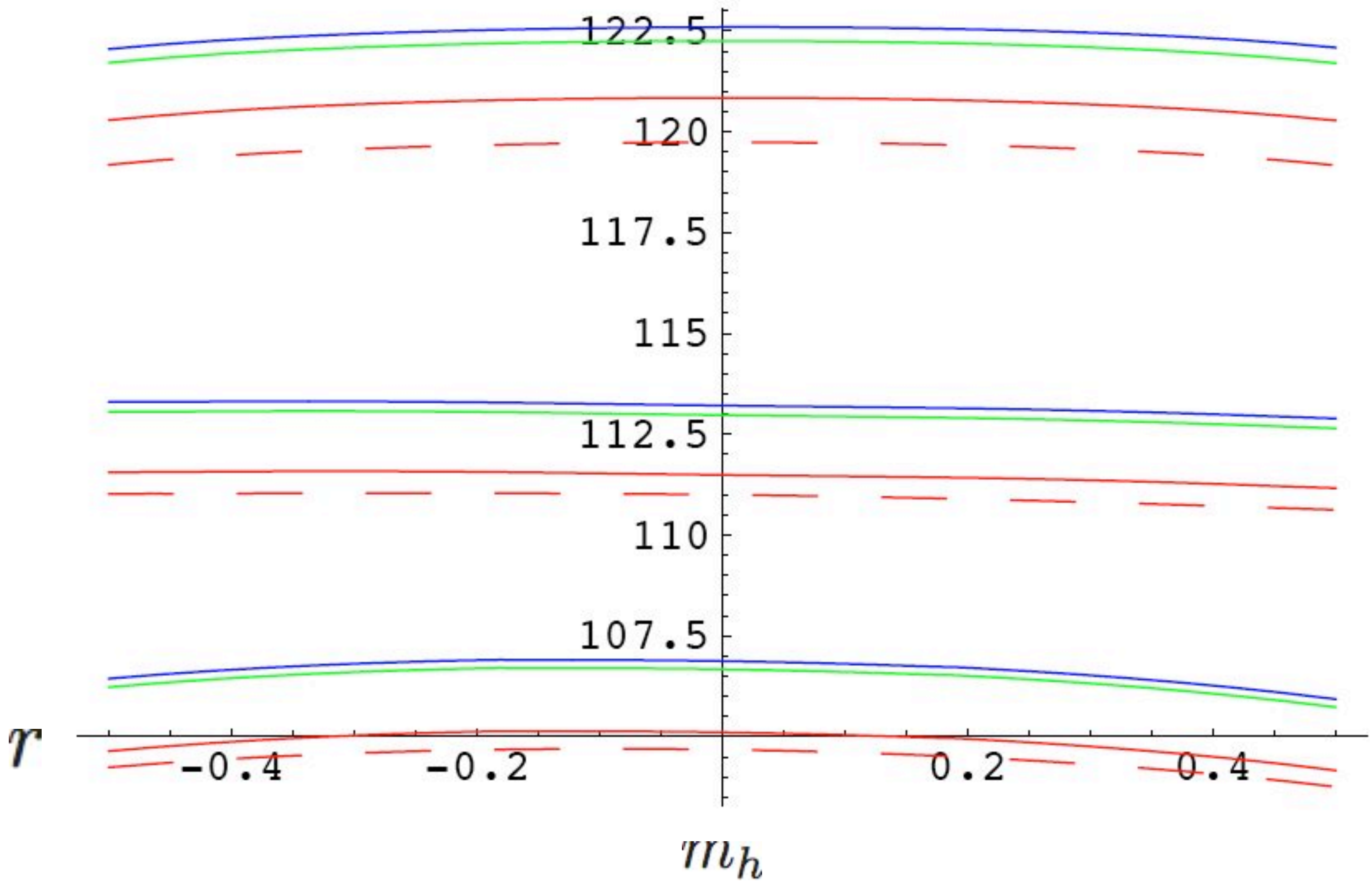


FIG. 3: Plot of the Higgs boson mass as a function of r for $m_{\tilde{t}}^2 = 500$ GeV, $\tan\beta = 10$ (red), $\tan\beta = 30$ (green), $\tan\beta = 50$ (blue) and $X_t/m_{\tilde{t}} = 0, -1, -2$ ordered from bottom up.The solid lines are $m_S = 400$ GeV and dashed lines are $m_S = 800$ GeV.

- As long as $| r | \leq 0.4$, neither the production rate nor the Higgs mass is very sensitive to r, the splitting in the soft-breaking masses.

- For $m_{\tilde{t}} = 500$ GeV,

$$m_{\tilde{t}_L} \sim 590 \text{ GeV and } m_{\tilde{t}_R} \sim 390 \text{ GeV}.$$

- In fact, all the Snowmass benchmark scenarios for SUSY, SPS1- SPS9, have stop mass splitting that fall within this range of r.

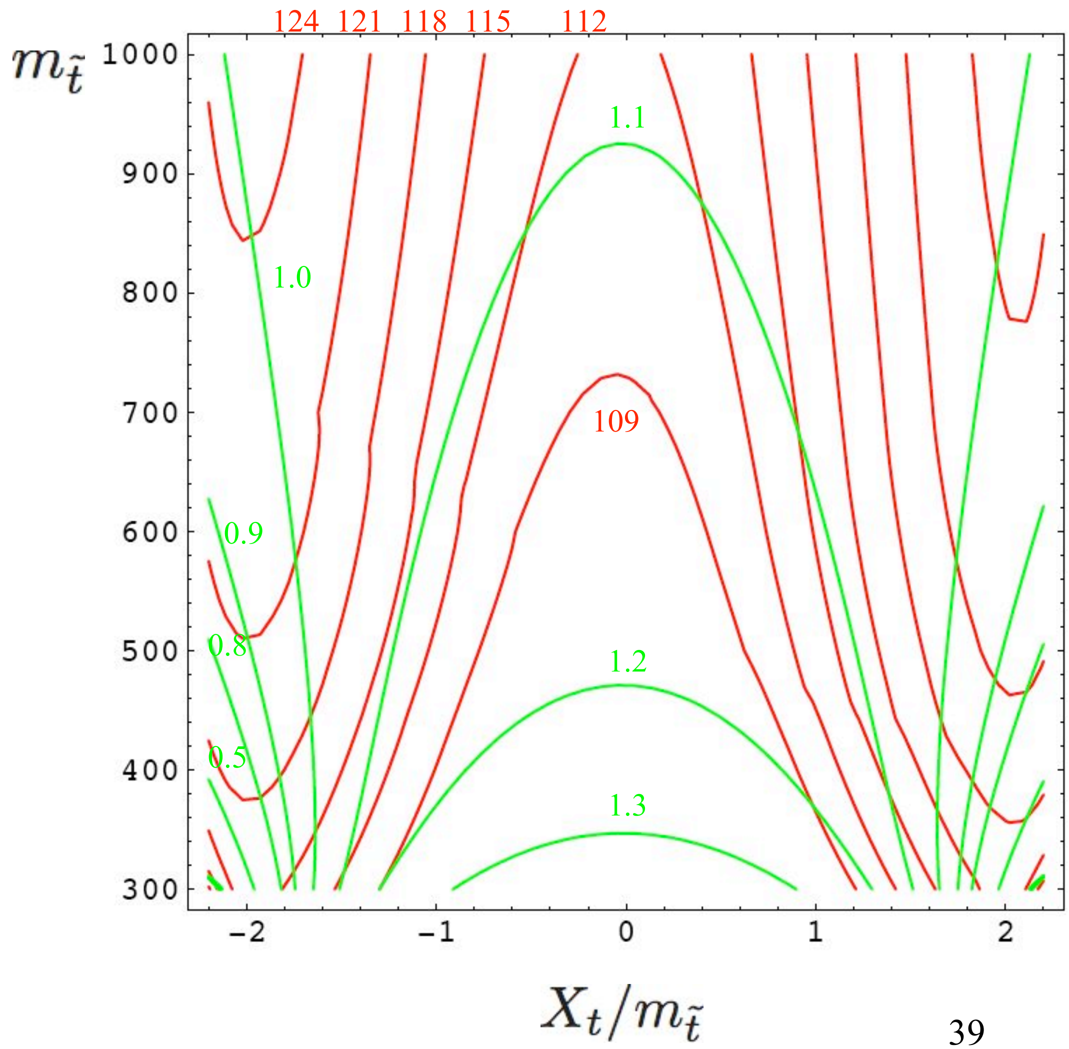
Now we can show contours of constant m_h (red contours) and R_g (green contours)

Some observations:

R_g alone seems to be a good indicator of the magnitude of mixing!

$R_g > 1$ if the mixing is small.
$R_g < 1$ if the mixing is large.

Production rate in MSSM is significantly reduced for light stops and large mixing, the region where some suggest is the less-fined region of MSSM.



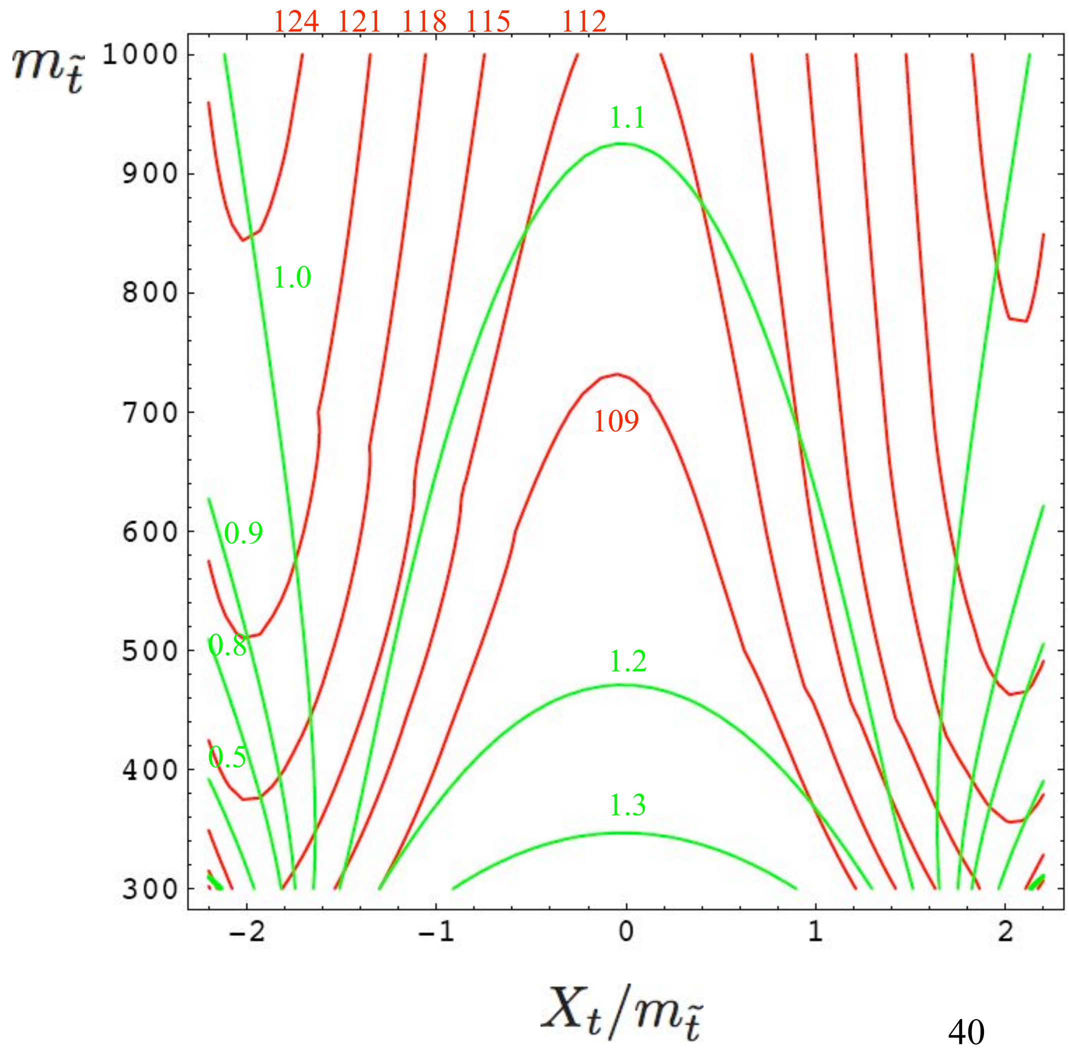
For small mixing in the stop sector contours of Higgs mass and production rate run somewhat parallel to each other.

$\rightarrow m_{\tilde{t}}$ is loosely constrained.

In this case the Higgs is light and production rate close to SM.

But if the stops are light and mixing large, the strategy is quite effective.

In this case the Higgs is light and production rate much smaller than SM!

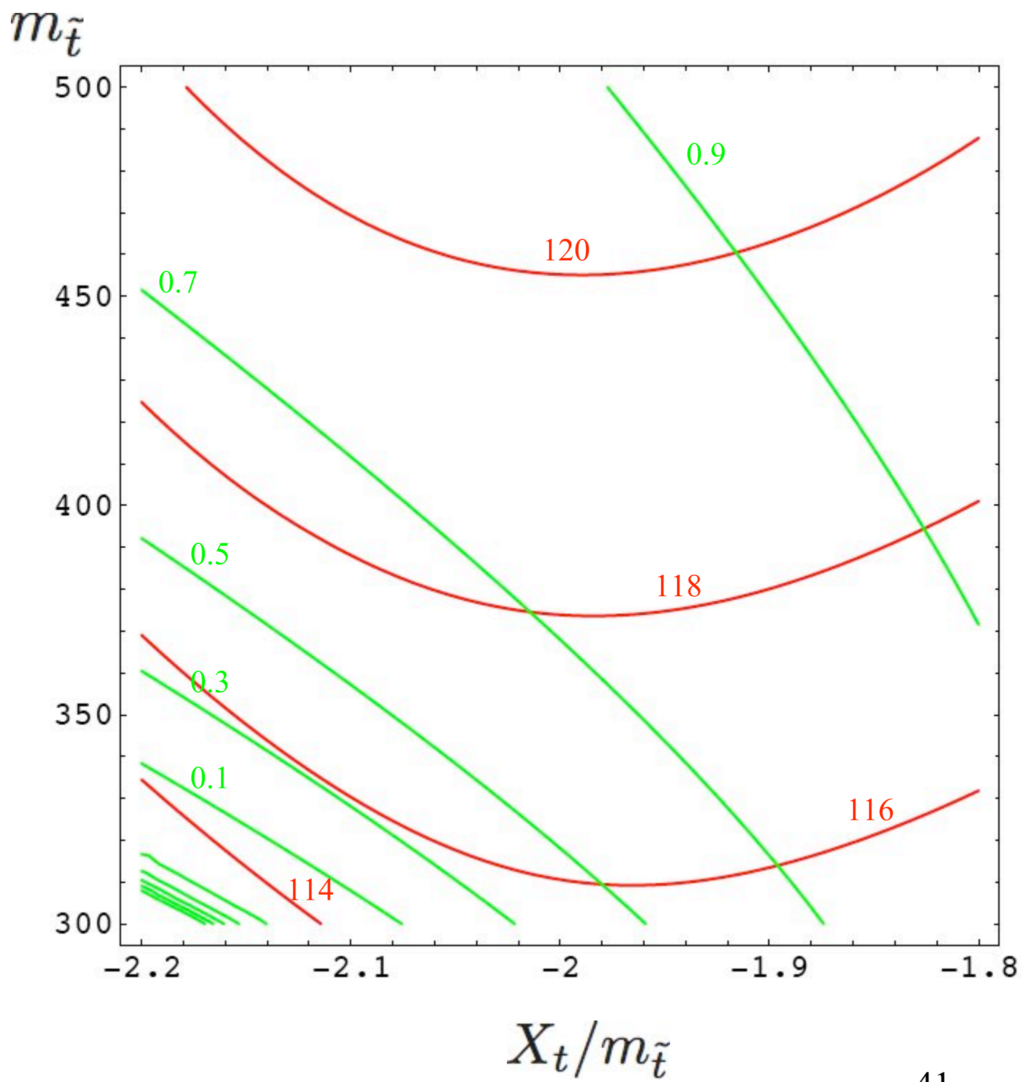


Let's zoom in on the corner of light stops with large mixing:

Even with a large uncertainty of 30% in the production rate, say $0.3 \le R_g \le 0.7$

With a precisely measured Higgs mass between 116 and 118 GeV, it is still possible to get a fairly constrained area for the overall stop mass scale and the mixing term.

All these are done with measurements in the Higgs sector only!



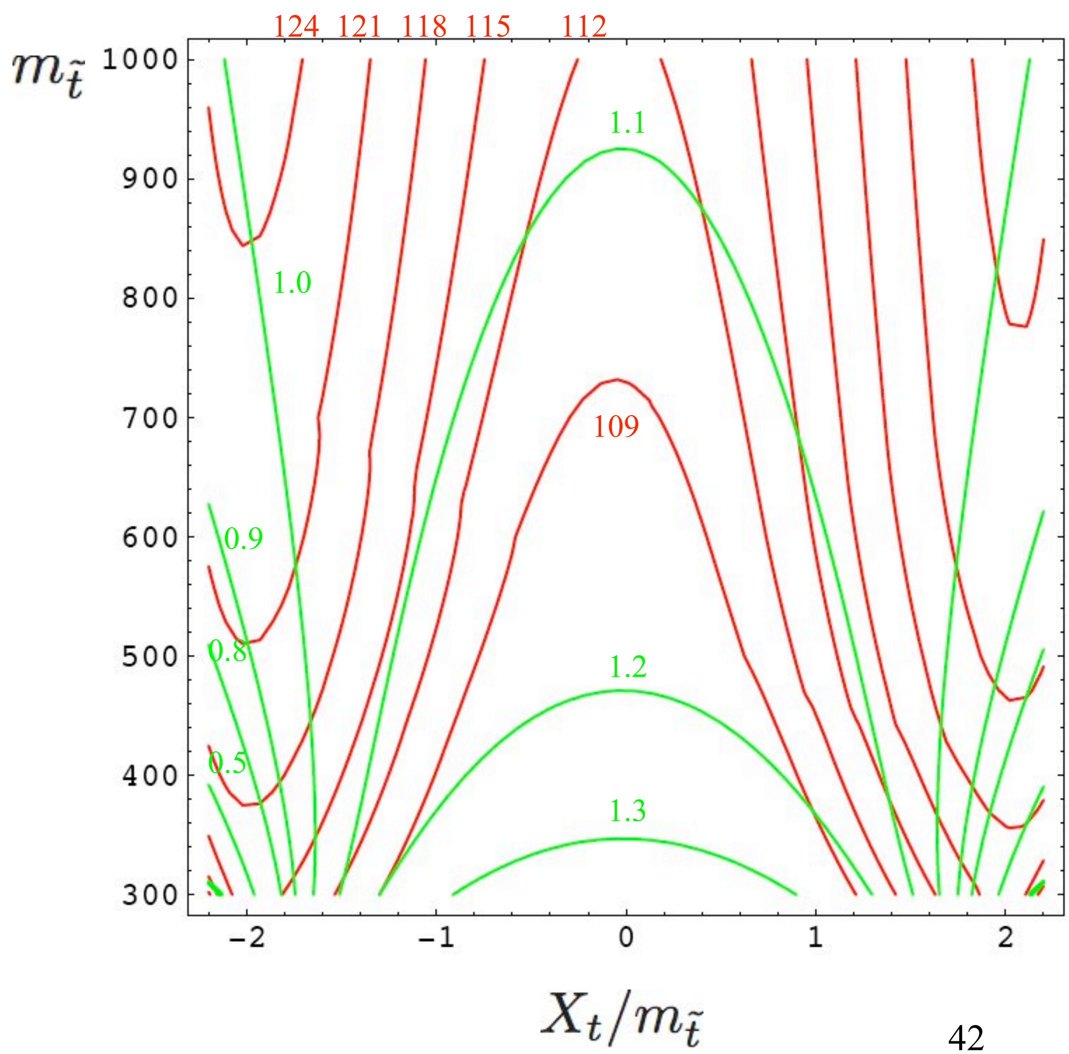
We can also explore the sanity of MSSM if the two measurements do not have overlapping contours.

Such a possibility could happen if the Higgs is heavy at around 130 GeV and the production rate much smaller than in the SM.

This implies the region of parameter space we are considering is disfavored.

But even if we do so, can we reconcile the differences within MSSM?

Need to consider regions where sbottom effect is important!



- It turns out that such a possibility is very difficult to reconcile within MSSM except in some insane corners of parameter space:

(a): $\tan\beta \sim 50$, $m_{\tilde{q}_3} \sim m_{\tilde{t}_R} \sim 2000$ GeV, $m_{\tilde{b}_R} \sim 100$ GeV, and $\mu \sim -800$ GeV.

(b): $\tan\beta \sim 50$, $m_{\tilde{q}_3} \sim m_{\tilde{b}_R} \sim 300$ GeV, $m_{\tilde{t}_R} \sim 5000$ GeV, and $\mu \sim -250$ GeV.

- Always need a hierarchy in and/or between the stop and sbottom sectors.

Such a pattern is very difficult to generate from known SUSY breaking mechanisms.

Message to take away:

- Stop sector is important for understanding the naturalness and consistency of MSSM, but its parameters are difficult to extract in production/decay processes at the LHC.

- Two measurements in the Higgs sector, mass and production rate, could provide access to the overall mass scale and mixing term in the stop sector.

- A relatively heavy Higgs mass and a significantly reduced production rate is difficult to reconcile within MSSM, except in extreme and insane corners of parameter space!

Non-supersummetric theories: naturalness in Higgs production/decay

Question: How can we find out if the underlying physics at the TeV scale is "natural" or not?

The "Who ordered that?" question!

If we observe new particles at the LHC, are they there to cancel the divergence in the Higgs mass?

Naively this seems a very difficult question because it requires precise measurements of coupling strengths as well as their signs, which are hard to do at the LHC.

But obviously this is a very important question!

- Nevertheless, we will argue that the Higgs boson is a very powerful probe for the naturalness of the underlying physics.

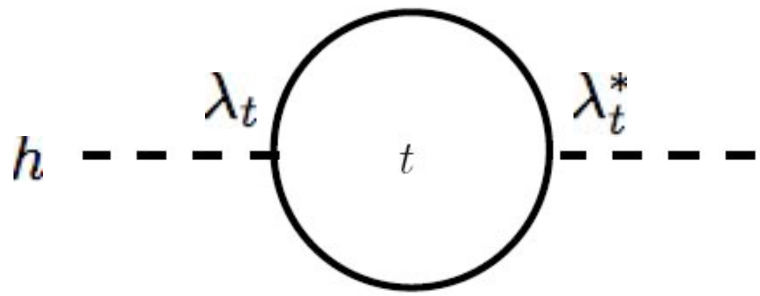
-- There's a deep connection between cancellation of Higgs divergences in the top sector and the production rate in the gluon fusion channel.

-- If $gg \to h \to \gamma\gamma$ rate is larger than standard model, a whole class of composite Higgs models (little Higgs, twin Higgs, holographic Higgs, gauge-Higgs unification) as well as "natural MSSM" would be strongly disfavored.

-- If $gg \to h \to \gamma\gamma$ rate is smaller than standard model, extra-dimensional models (UEDs) and "unnatural MSSM" would be ruled out immediately.

- The statement is based on the following observation:

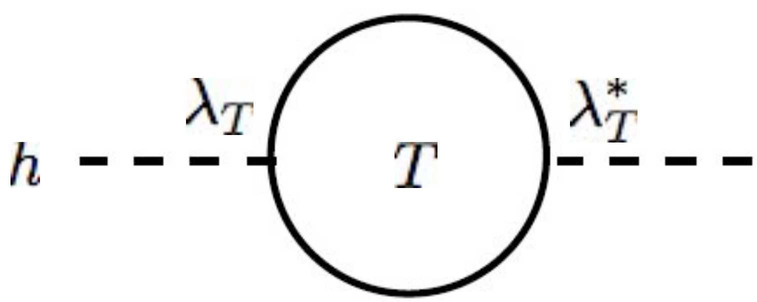
The interaction of the Higgs with the top quark induces a quadratically divergent contribution in the Higgs mass:



$$= -\frac{3}{8\pi^2}|\lambda_t|^2\Lambda_{\rm NP}^2$$

Q: How do we use another fermion to cancel the above divergence?

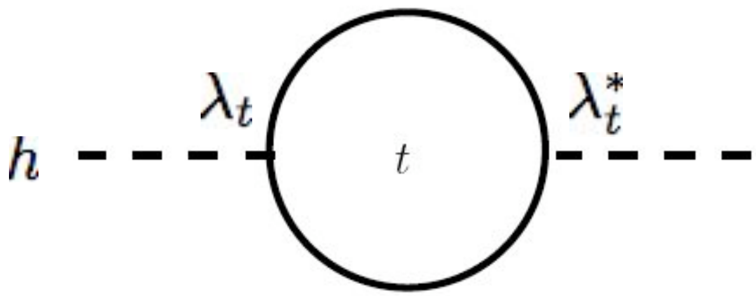
Wrong answer: another fermion *T* with only Yukawa coupling to the Higgs wouldn't work. The divergences always add up!



$$= -\frac{3}{8\pi^2}|\lambda_T|^2\Lambda_{\rm NP}^2$$

- The statement is based the following observation:

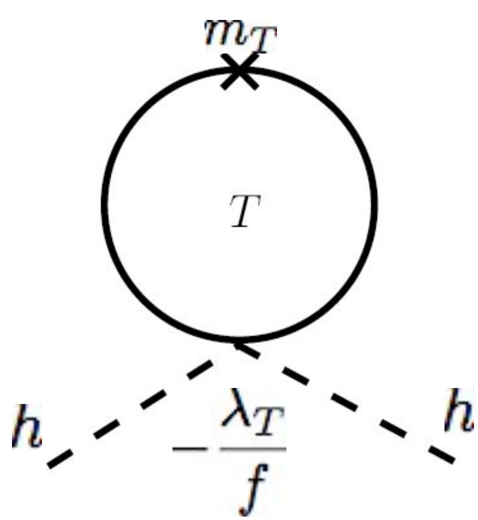
The interaction of the Higgs with the top quark induces a quadratically divergent contribution in the Higgs mass:



$$= -\frac{3}{8\pi^2}|\lambda_t|^2\Lambda_{\mathrm{NP}}^2$$

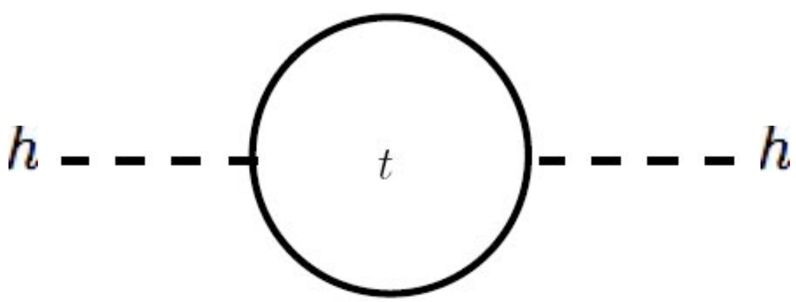
Q: How do we use another fermion to cancel the above divergence?

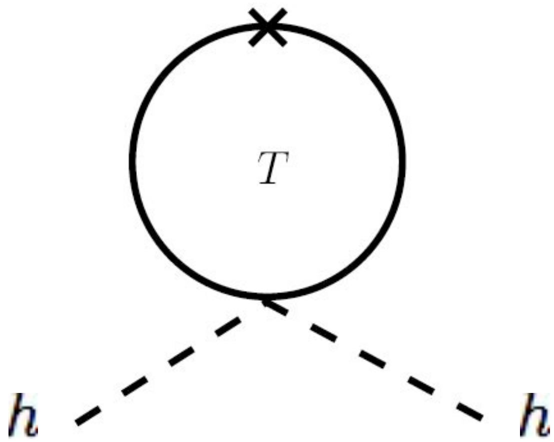
Correct answer: always need a dimension-five coupling with the Higgs!



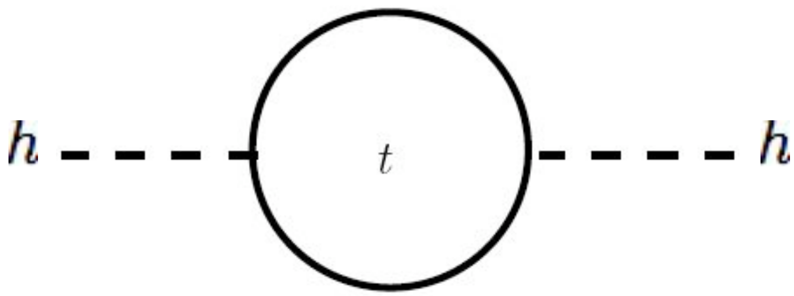
$$= -\frac{3}{8\pi^2}\left(-m_T\frac{\lambda_T}{f}\right)\Lambda_{\mathrm{NP}}^2$$

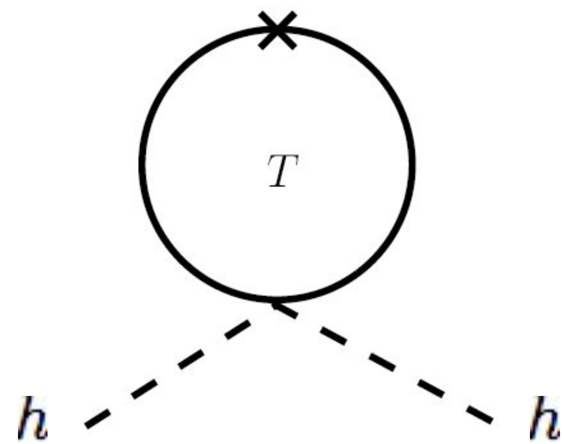
- If the following two diagrams have a relative minus sign, then Higgs quadratic divergence is cancelled. Otherwise, the divergences add up.





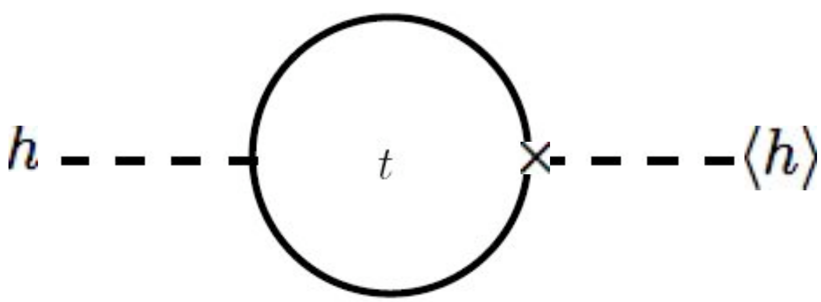
Now let's massage the diagrams a little bit:

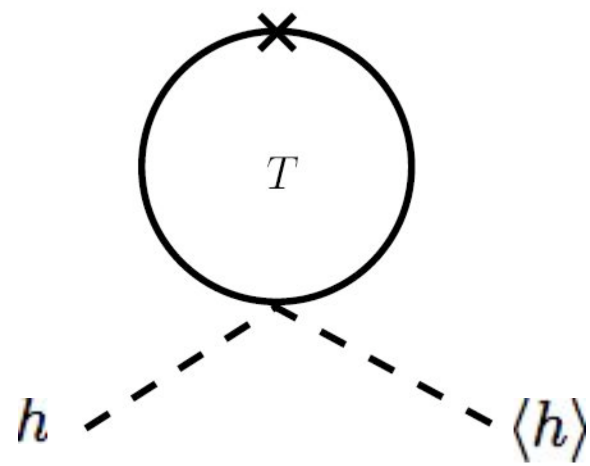




Now let's massage the diagrams a little bit:

-- First putting one of the Higgs field in its VEV.

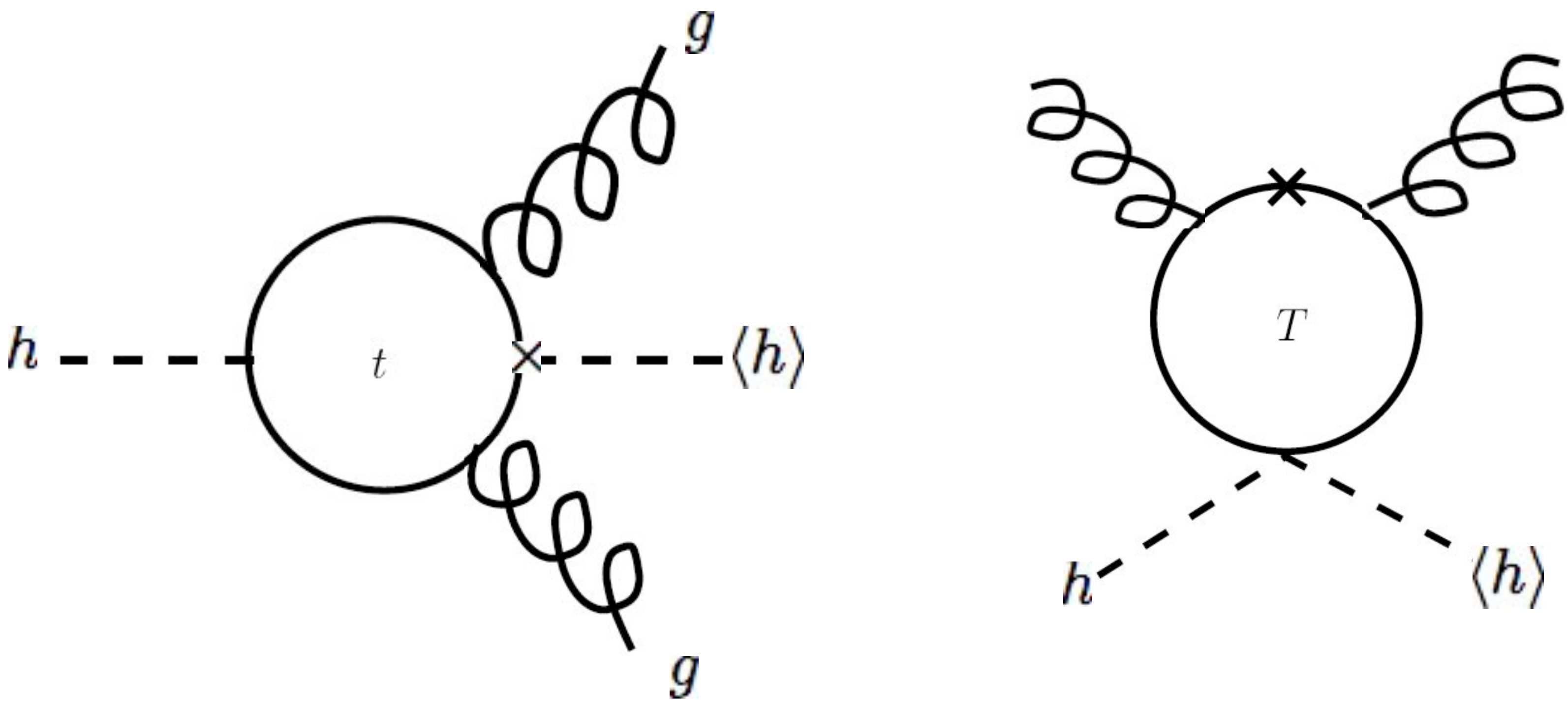




Now let's massage the diagrams a little bit:

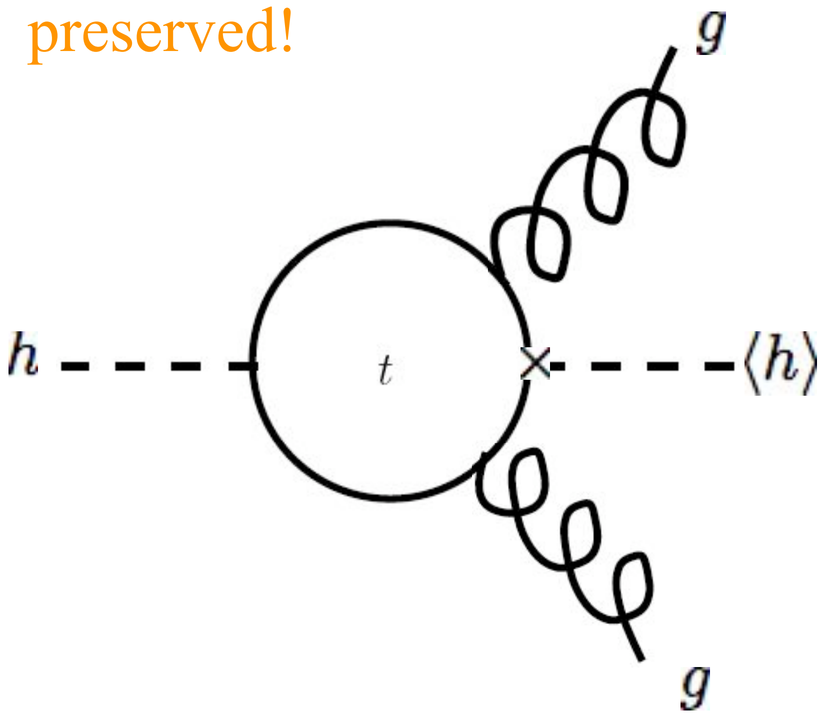
-- First putting one of the Higgs field in its VEV.

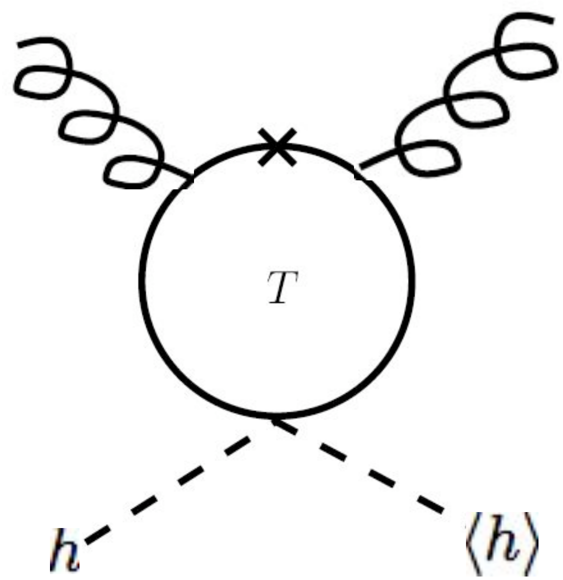
-- Next let's insert two gluons into the fermion line.



These are exactly the two diagrams contributing to gluon fusion from the top quark and the new state!

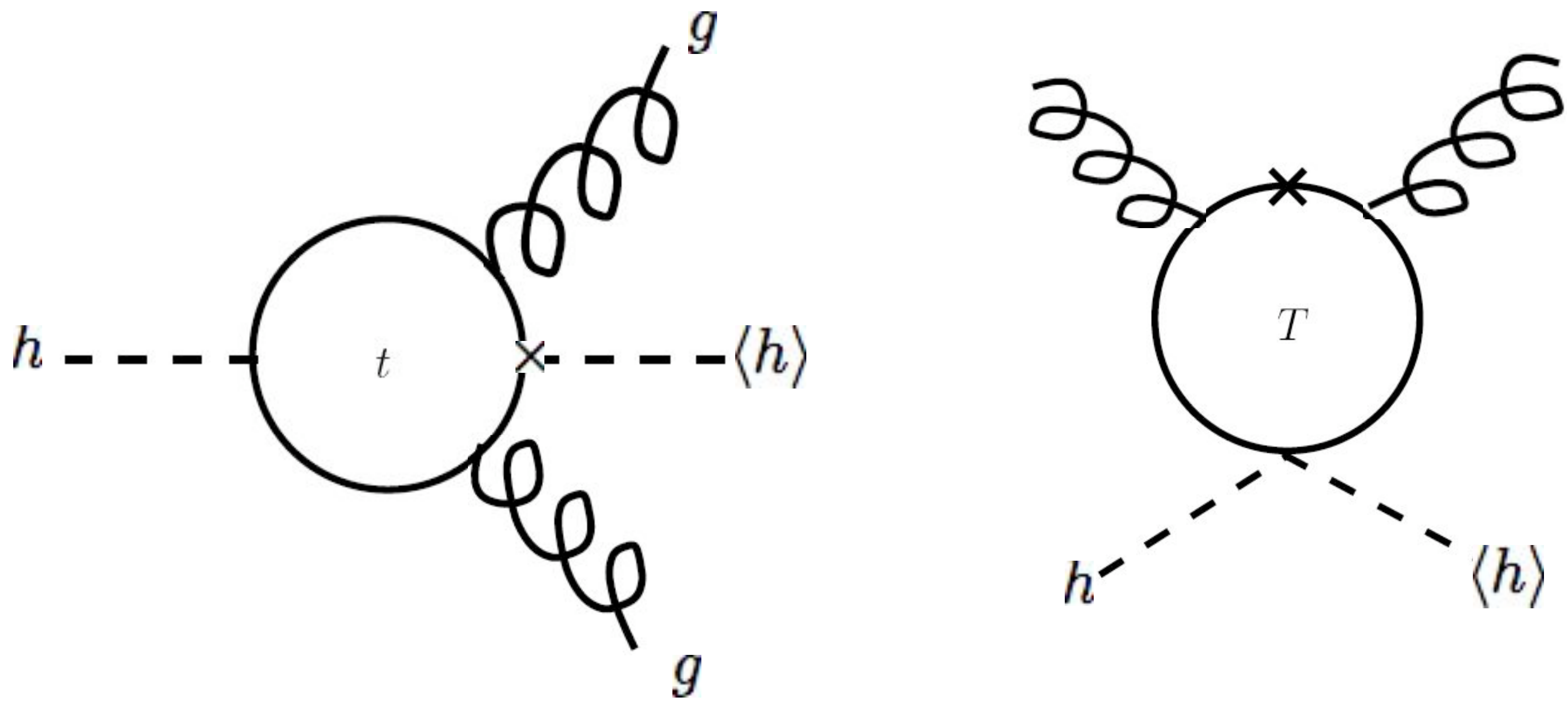
Because we have the same number of insertions along the fermion line, the relative sign between the diagrams is preserved!



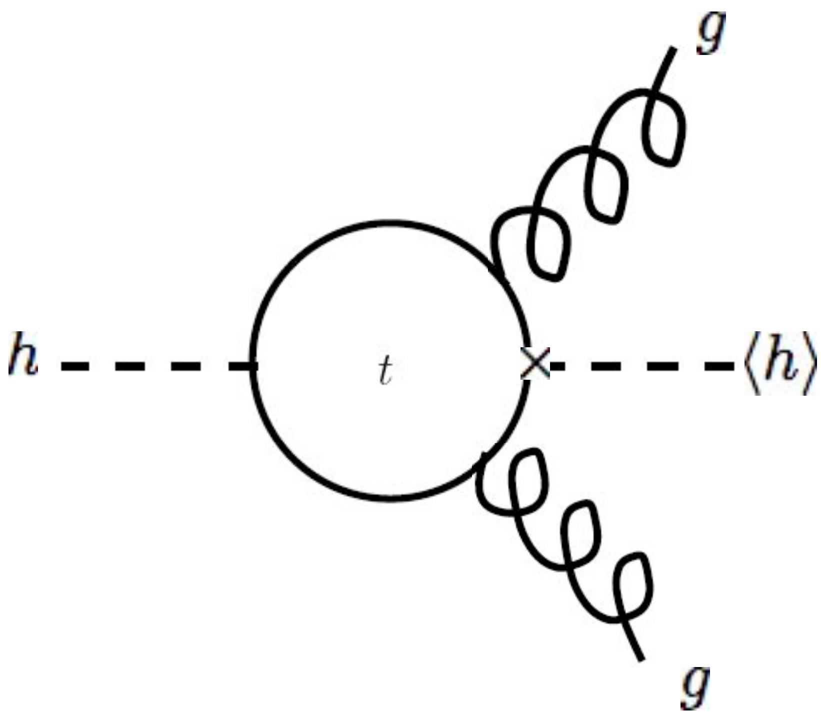


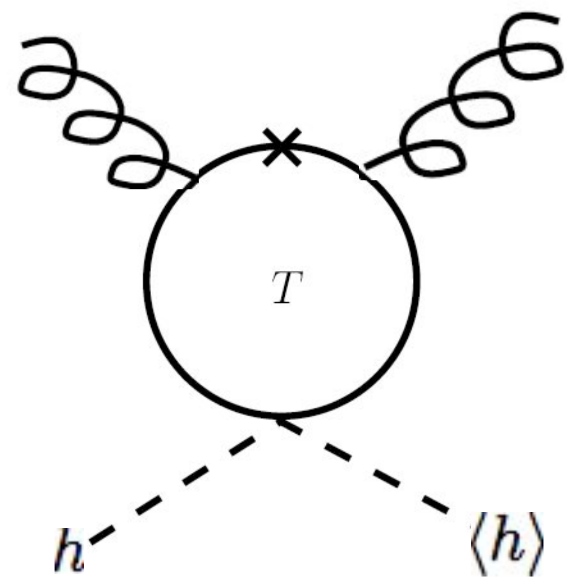
In other words, if the Higgs divergence is canceled, the new state would interfere <u>destructively</u> with the top quark.

But if the divergence is NOT canceled, the new state would interfere <u>constructively</u> with the top quark.



The only assumption here is there is a new degree of freedom that is colored and has a significant coupling to the Higgs. Otherwise, our statement is completely general, model independent, and applies to any non-supersymmetric theories.





- Could generalize the diagrammatic argument to include mixings between the top quark and the new heavy state, or scalar partners (SUSY!).

(Using Coleman-Weinberg potential and low-energy theorems of the Higgs.)

- Opposite to the fermionic case, a scalar partner (stop!) would interfere <u>constructively</u> with the top in the production rate if it cancels the Higgs divergence, and <u>destructively</u> otherwise.

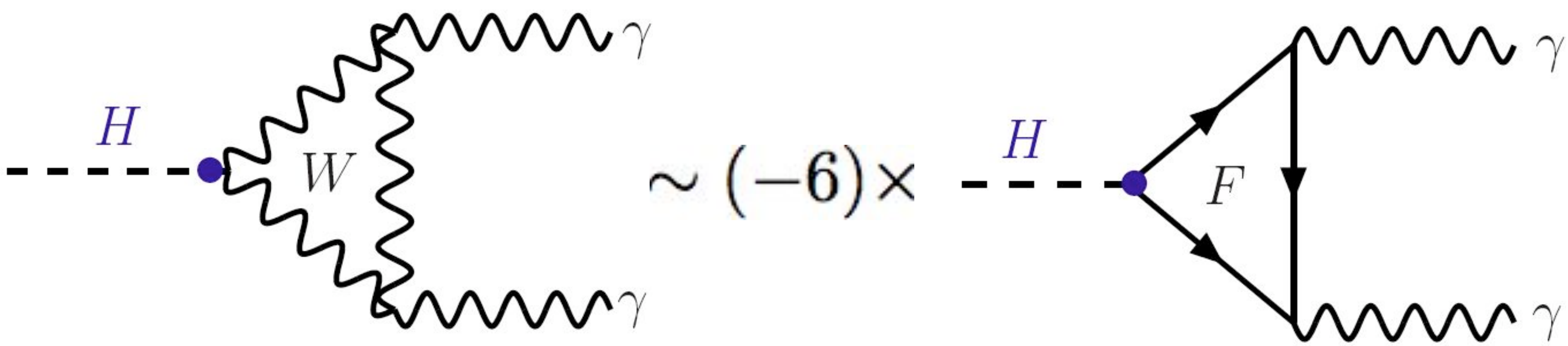
- If there are two scalar partners (two stops!), a mixing term could decrease the production rate. A large mixing term could turn the <u>constructive</u> interference into <u>destructive</u>.

- In the end, for non-supersymmetric theories, $R_g < 1$ if the model is natural, which includes a whole class of composite Higgs models. (eg little Higgs, holographic Higgs, twin Higgs, gauge-Higgs unification, etc.)

- $R_g > 1$ if the model is unnatural. That is the case if the top-like state is simply a Kaluza-Klein mode of the standard model top quark, such as in extra dimensional models. (eg UEDs.)

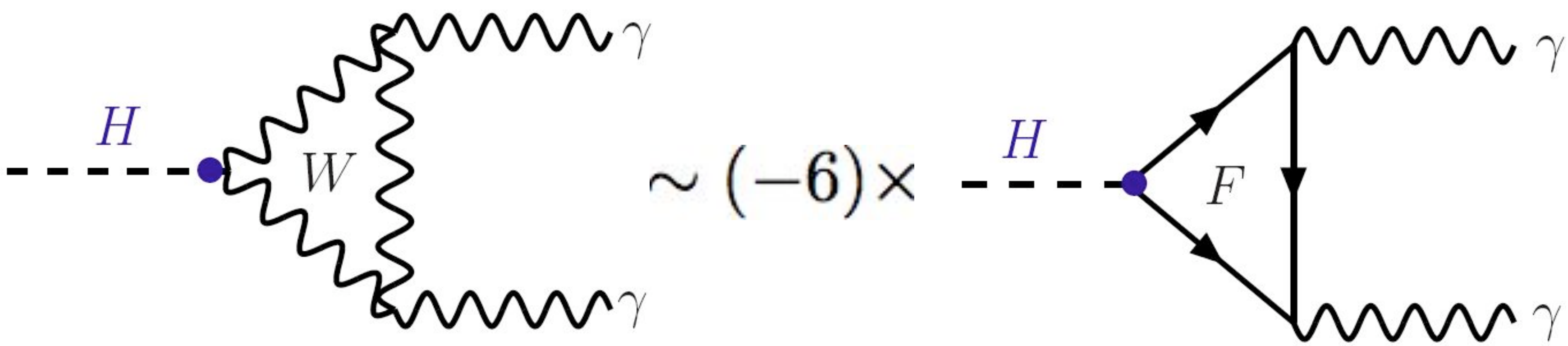
- That was for the gluon fusion production rate, which is not directly observable and has a large uncertainty.

- It is possible to make a similar statement for the role of the top-like new state in the di-photon decay mode of the Higgs.



- For di-photon decay the *W* boson loop dominates, even though the top loop contributes with an opposite sign.

- A new top-like heavy state could have an effect, but it's going to be smaller than in the gluon fusion production.



- Moreover, the even rate of $gg \to h \to \gamma\gamma$ is determined by

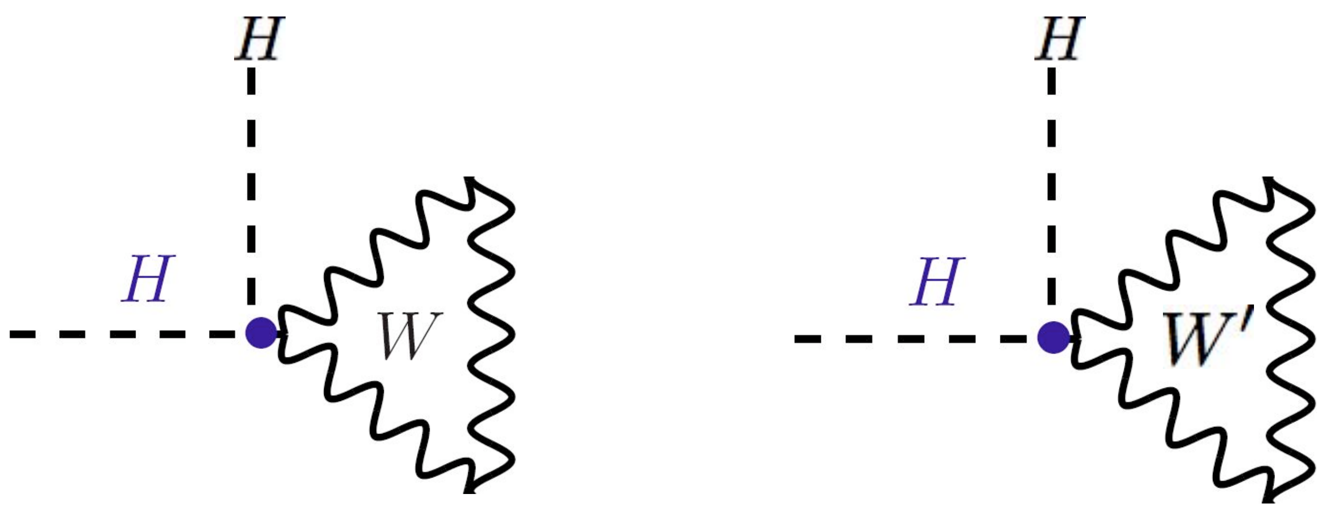
$$\sigma(gg \to h) \times Br(h \to \gamma\gamma) \propto \Gamma_g \frac{\Gamma_\gamma}{\Gamma_{\rm tot}}$$

Therefore we expect the ratio of the even rate with the standard model should be largely determined by the ratio

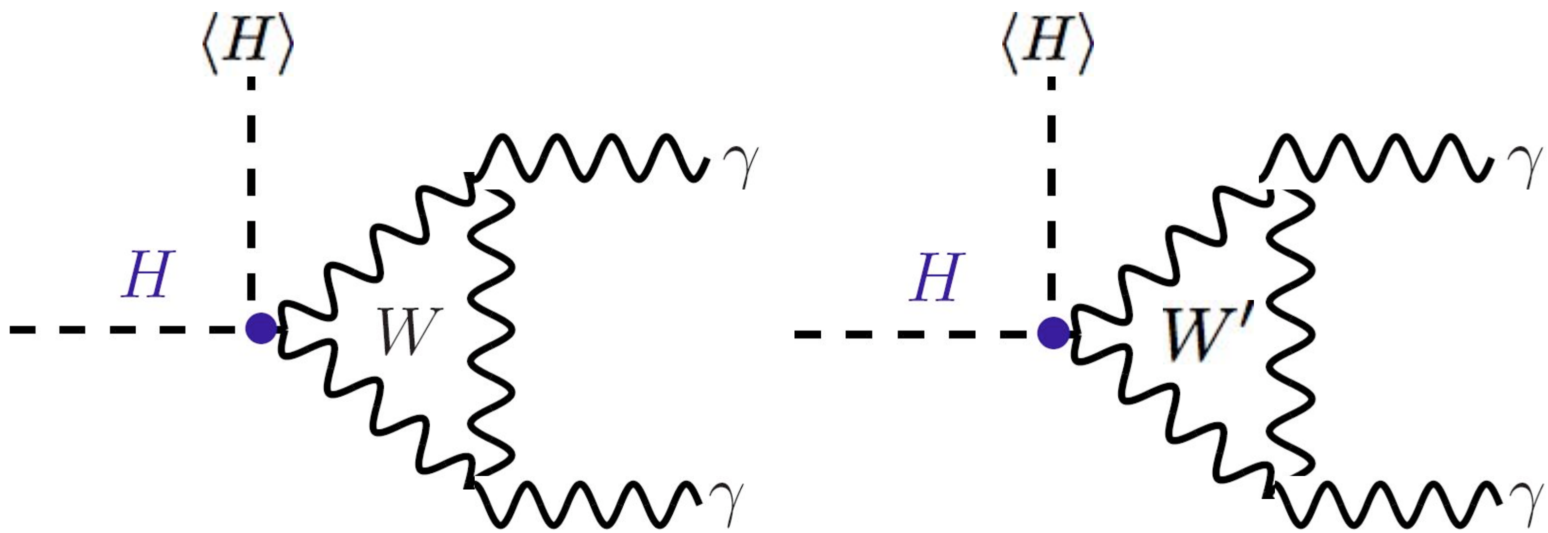
$$\frac{\Gamma_g^{\rm BSM}}{\Gamma_g^{\rm SM}} > 1 \quad \text{or} \quad < 1\ ?$$

So far this is assuming only new top-like states.

- Next consider, in addition to the top-like states, there's a new heavy gauge boson contributing to the Higgs divergences.
- Again we can massage the diagrams in the same fashion:

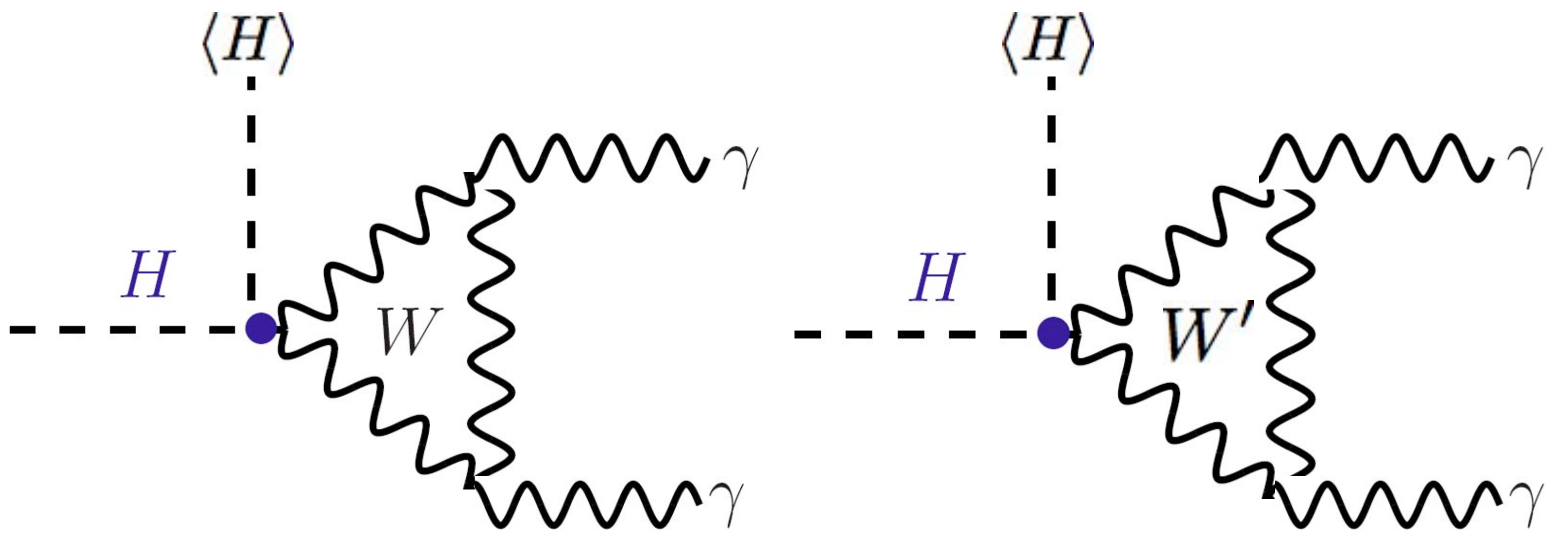


- Next consider, in addition to the top-like states, there's a new heavy gauge boson contributing to the Higgs divergences.
- Again we can massage the diagrams in the same fashion:



- Then these are the diagrams contributing to the di-photon decay of the Higgs.

- Again the relative sign is preserved in going from the Higgs divergence to the di-photon decay.



- Similar the gluon fusion production, for non-supersymmetric theories the ratio of di-photon decays $R_\gamma <$ 1 if the model is natural.

- $R_\gamma > 1$ if the model is unnatural.

In the end if there are new top-like states as well new heavy gauge bosons, both R_g and R_γ are less than unity if there is naturalness in the model and greater than unity if there's none.

Same can be said about $B\sigma(gg \to h \to \gamma\gamma)$!

Message to take away:

- If at the LHC we measure

$$\frac{B\sigma^{\mathrm{BSM}}(gg \to h \to \gamma\gamma)}{B\sigma^{\mathrm{SM}}(gg \to h \to \gamma\gamma)} > 1$$

then unnatural models such as UEDs and MSSM with small mixing in the stop sector are favored.

- If on the other hand we measure

$$\frac{B\sigma^{\mathrm{BSM}}(gg \to h \to \gamma\gamma)}{B\sigma^{\mathrm{SM}}(gg \to h \to \gamma\gamma)} < 1$$

then natural models such as composite Higgs and MSSM with large mixing in the stop sector are favored.

- Assuming no supersymmetry:

  If the ratio of partial widths $R_g < 1$, there's a new top-like fermionic state canceling the top quadratic divergences in the Higgs mass.

  If the ratio $R_\gamma < 1$, there's a new vector boson canceling the gauge quadratic divergence in the Higgs mass.

Conclusion:

- There’s a surprising amount of information one can extract from measurements in the Higgs sector alone.
- Such information is difficult to extract otherwise at the LHC, and could provide some direction for experiments at the International Linear Collider.
- Given the (sometimes) large uncertainties, now there’s strong motivation to improve on both experimental strategies and theoretical computation.